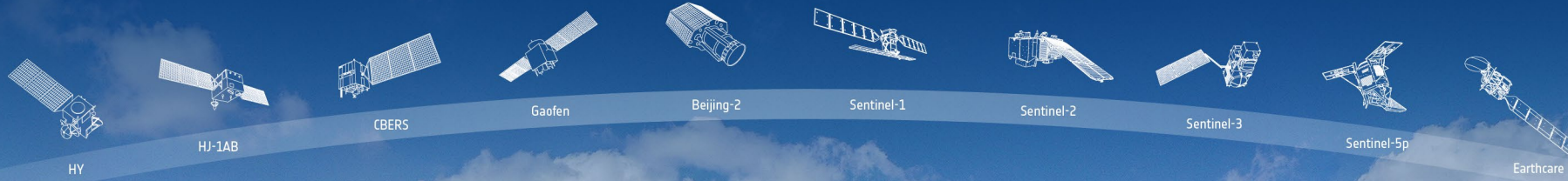




中国科学技术交流中心
China Science and Technology Exchange Center



→ THE EUROPEAN SPACE AGENCY



2025 DRAGON 6 SYMPOSIUM

14-18 JULY 2025

[PROJECT ID. 95437]

[VALIDATION AND APPLICATION OF OBSERVATIONS FROM MULTIPLE LOW EARTH ORBITAL SATELLITES FOR MONITORING THE EARTH'S MAGNETIC AND PLASMA ENVIRONMENT]





<WEDNESDAY, 16/JULY/2025>

ID. 95437

PROJECT TITLE: Validation and application of observations from multiple low Earth orbital satellites for monitoring the Earth's magnetic and plasma environment

PRINCIPAL INVESTIGATORS: [Claudia Stolle and Chao Xiong]

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PRESENTED BY: [Chao Xiong]

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Assistant Prof.	Kuan	Li	MISTA-Macau Institute of Space Technology and Application
Prof.	Rui	Yan	NINH-National Institute of Natural Hazards, Ministry of Emergency Management of China
Associate Prof.	Fan	Yin	WHU-Wuhan University
Associate Prof.	Yunliang	Zhou	WHU-Wuhan University
Associate Prof.	Yanyan	Yang	NINH-National Institute of Natural Hazards, Ministry of Emergency Management of China
Associate Prof.	Dapeng	Liu	NINH-National Institute of Natural Hazards, Ministry of Emergency Management of China
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- **The project's objectives**
- **The data utilised to achieve the project's objectives**
- **Outcomes of the project in the last year**
 - **Analysis of satellite magnetic data**
 - **Ionospheric current inversion and modeling**
 - **3D ionospheric modeling**
- **List of Publications**

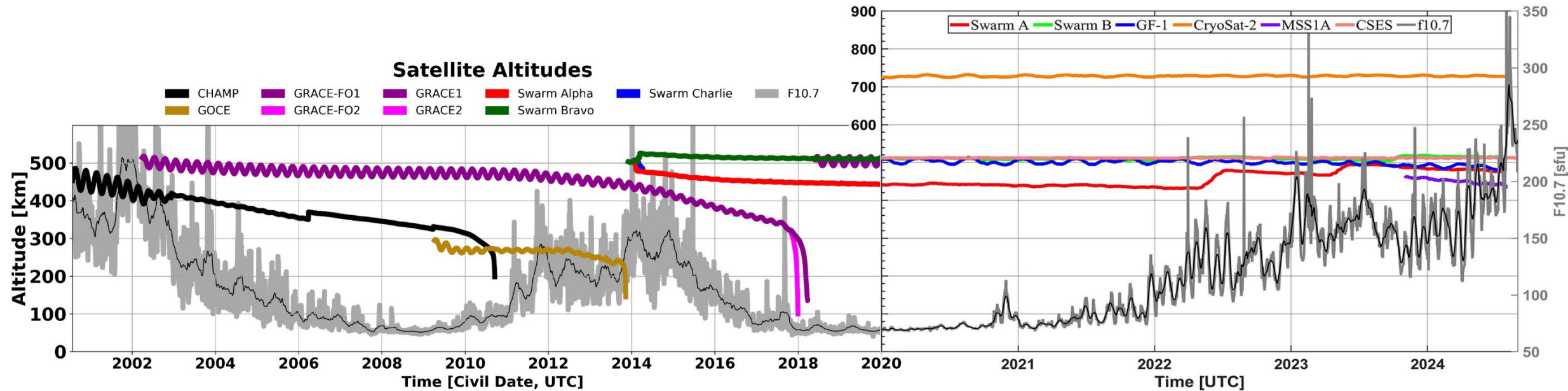


- 1) Cross-calibration and validation of **magnetic field and ionospheric plasma parameters** observations among Swarm, CSES and MSS-1 satellites. Joint development of algorithms to eliminate the artificial influences from these platforms.
- 2) Joint comparison of the simultaneous measurements from Swarm, CSES and MSS-1, during **different space weather conditions**, such as magnetic quiet and disturbed periods, solar flare and eclipse events etc., to fully evaluate the performances of all three satellites.
- 3) Joint analyze data from these different LEO missions, and use of the well-calibrated magnetic and electric data to derive variables/indices for the **magnetospheric and ionospheric currents**, e.g., ring currents, FACs, Sq and EEJ.
- 4) Joint use of the plasma density from multi-LEO missions to develop **empirical models**, e.g., three-dimensional electron density models, plasma irregularities and scintillation models, EEJ and Sq models etc., for representing the climatologic and near-real time magnetic/plasma environment of the Earth.



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low Earth orbital satellites



Europe: CHAMP、Swarm

China: CSES、MSS

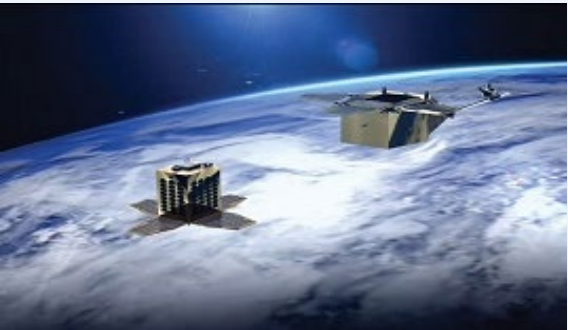
Other: GOCE、GRACE/FO、CryoSat

Swarm	2013-11-22
张衡一号 (China Seismo-Electromagnetic Satellite, CSES)	2018-02-02
澳门科学卫星一号 (Macau Science Satellite, MSS)	2023-05-21

MSS and Swarm

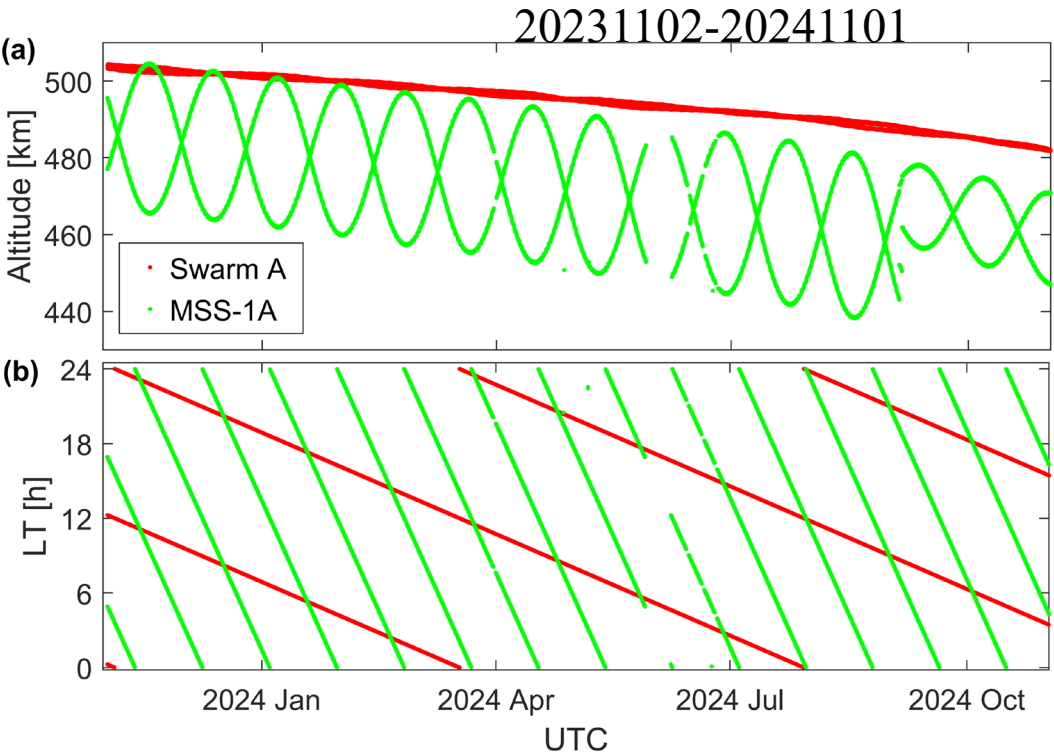


MSS-1A 41°inclination



<https://mss.must.edu.mo>

Swarm A 87° inclination



(a) Orbit altitude of MSS-1A's equatorial crossing. (b) Local time of MSS-1A's equatorial crossing.

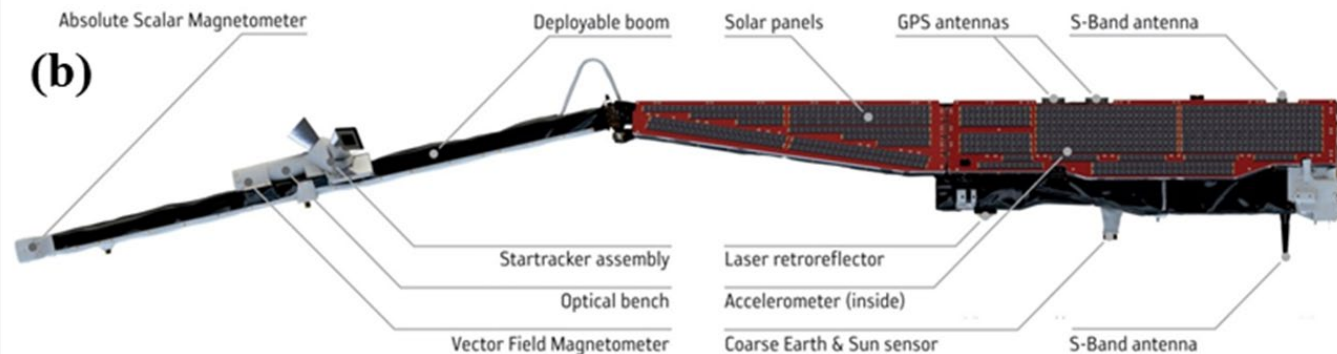
	Altitude reduction	Orbital period	Orbital regression period
MSS-1A	50 km	1.56 hours	26.14 days
Swarm A	20 km		132.45 days
	Elevated solar activity leads to higher atmospheric drag		Low-inclination MSS-1A: Sample the magnetic field at all local times in a relatively short period



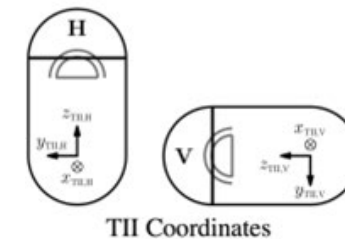
(a)



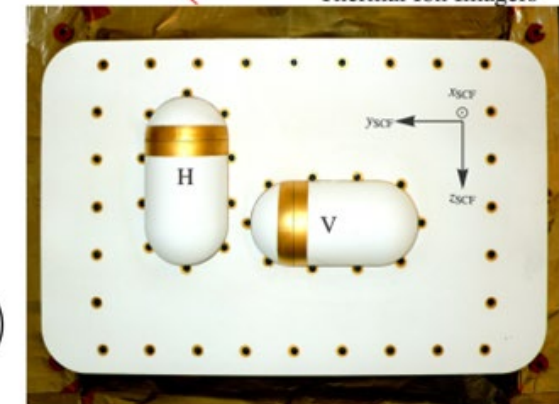
(b)



Langmuir Probes



Thermal Ion Imagers

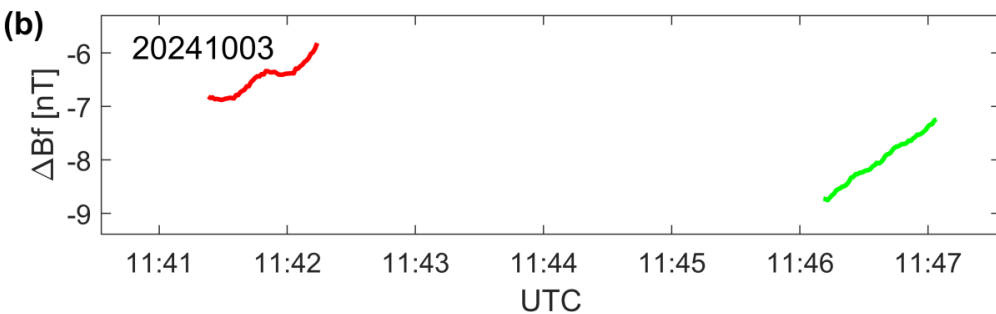
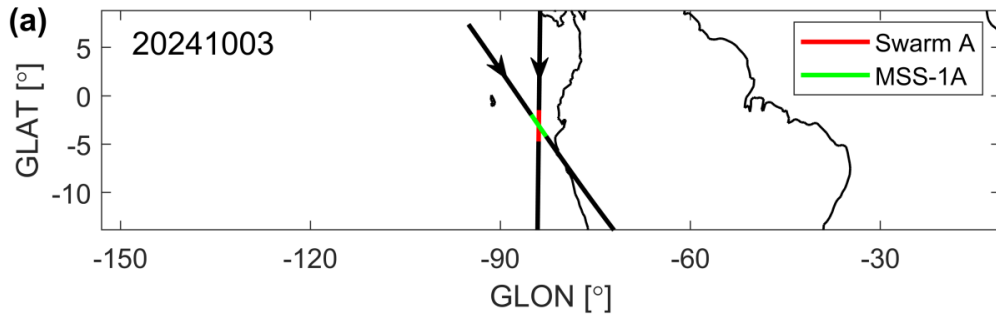


Vector Field Magnetometer (VFM)、Absolute Scalar Magnetometer (ASM)、Electric Field Instrument、Star Tracker and Laser Retroreflector、GPS Receiver、Accelerometer、Langmuir Probes and Thermal Ion Imagers

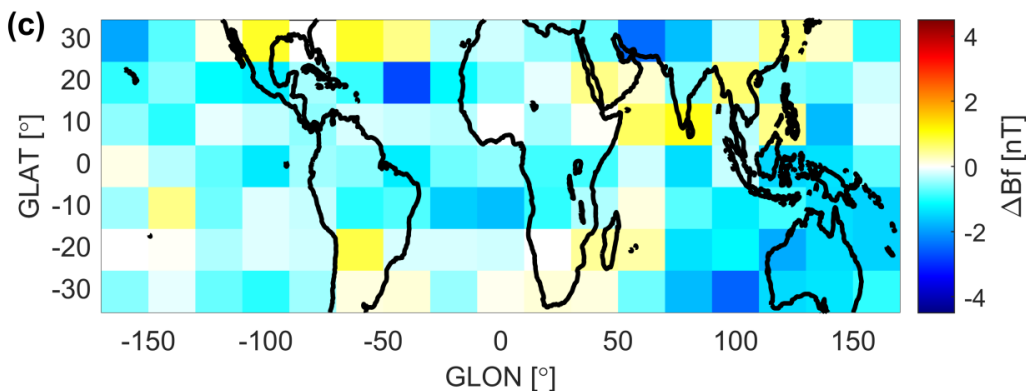


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Conjunction events



“Conjunction”:
 $\Delta t < 5$ min and
 $\Delta R < 150$ km



Event analysis

The two satellites intersect at approximately 3°N latitude and 84°E longitude, with Swarm A crossing the location at around 11:42 UTC and MSS-1A crossing at approximately 11:47 UTC.

The average of the magnetic residuals between the two satellites is only about **2** nT.

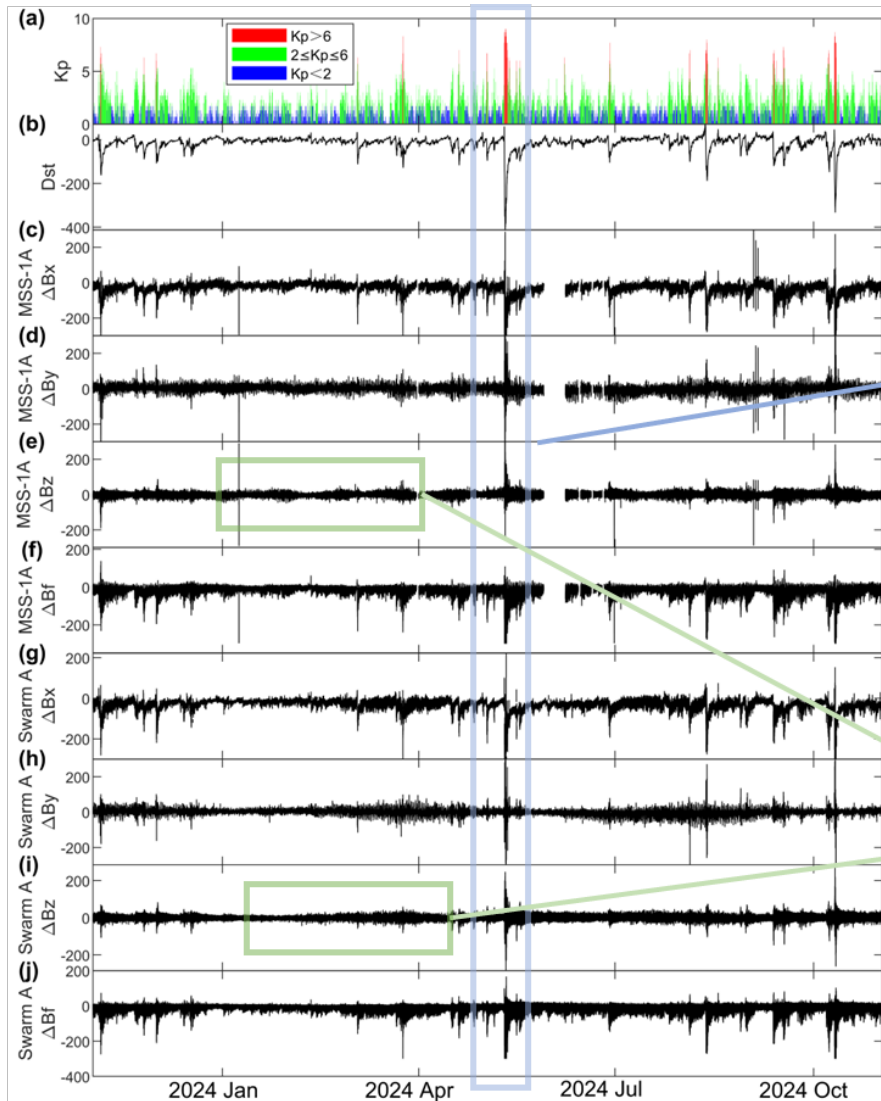
Statistic

20231102-20241101: 1,116 conjunction events.

The majority of the total residuals show variations within only **±1.5** nT. Such small differences between the MSS-1A and Swarm A observations further support the high quality of the magnetic data set of the MSS-1A mission.

Trajectory of a conjunction event, with the total residual magnetic field. (c) Geographic distribution of the total residuals from all conjunction events.

Natural signals



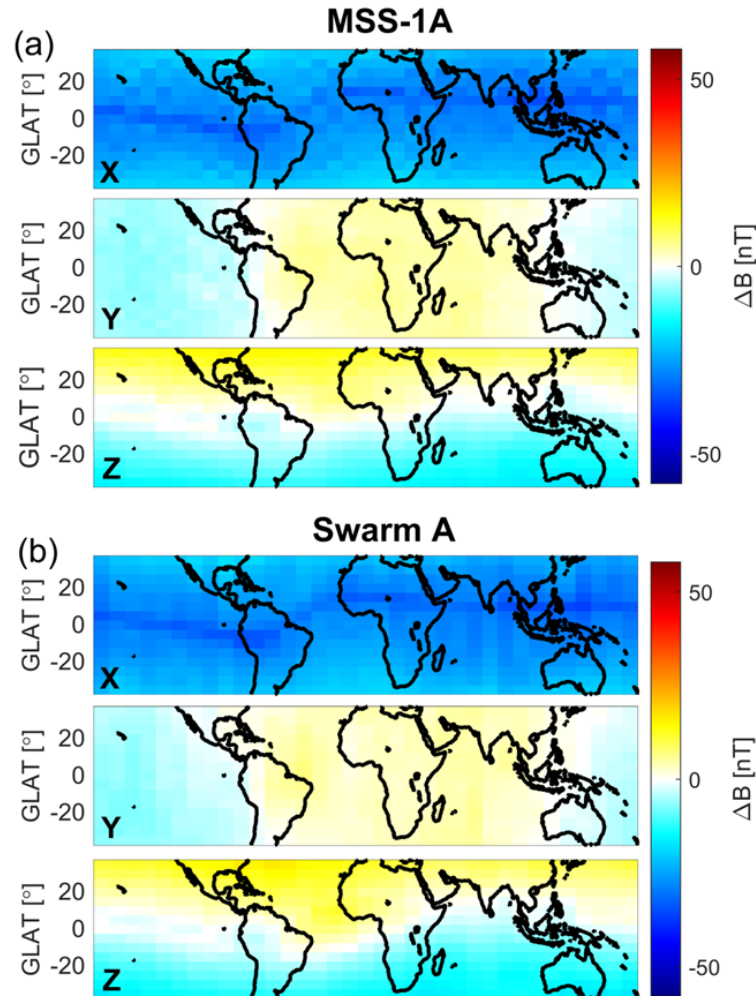
Both satellites exhibit substantial disturbances during geomagnetic storms, such as those on November 5, 2023, **May 10, 2024**, August 12, 2024, and October 10, 2024, with the residual total magnetic field reaching up to 200 nT. The enhancement is caused by ring current.

During geomagnetically quiet periods, the residual geomagnetic field components for both satellites remain within the range of tens of nT. This is primarily caused by the magnetic effects of magnetospheric currents and ionospheric currents.

“Envelope structure” is related to orbital precession period.

Magnetic residuals to CHAOS-7 predictions (core and lithospheric field) in the NEC frame.

Natural signals



- *X*-component:

An intense, narrow band that flows above the magnetic dip equator, with a magnitude of approximately 40 nT: **EEJ**

- *Y*-component:

The signature primarily exhibits east-west variations, with negative values to the west of -70°E and positive values to the east: **magnetic declination**

- *Z*-component

The directions are reversed across the magnetic equator, with a magnitude of approximately 10 nT in both hemispheres: **current (e.g. ring current, EEJ)**

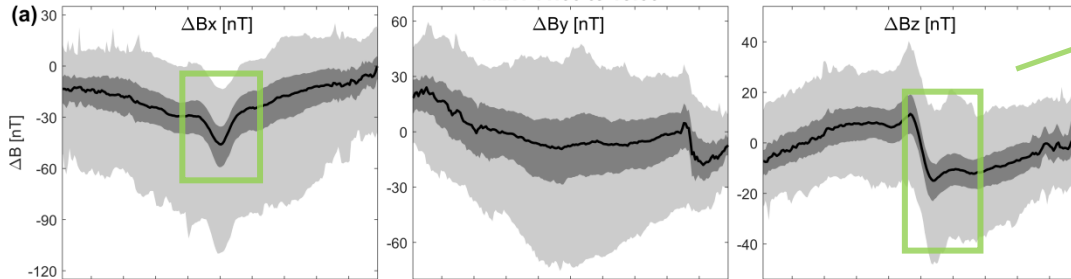
Overall, the distribution maps of the three magnetic field components from MSS-1A and Swarm A are quite similar.

The geographic distribution is represented by the median of all residuals within each grid bin with a bin size of 5° GLAT and 10° GLON.

Natural signals

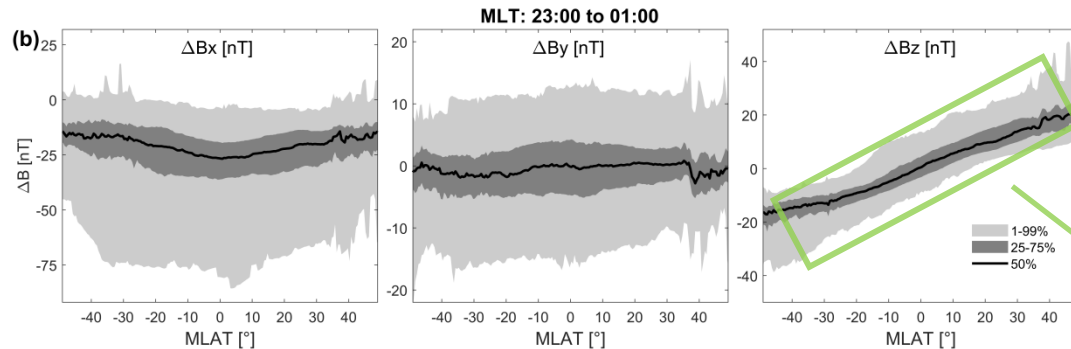


MSS-1A from 20231102 to 20241101
MLT: 11:00 to 13:00



EEJ

Significant variations in the X- and Z-components of the magnetic field are observed near the magnetic equator. The amplitudes in both components, approximately 20 nT, are consistent with the previous research (Lühr and Maus, 2006; Stolle et al., 2021).



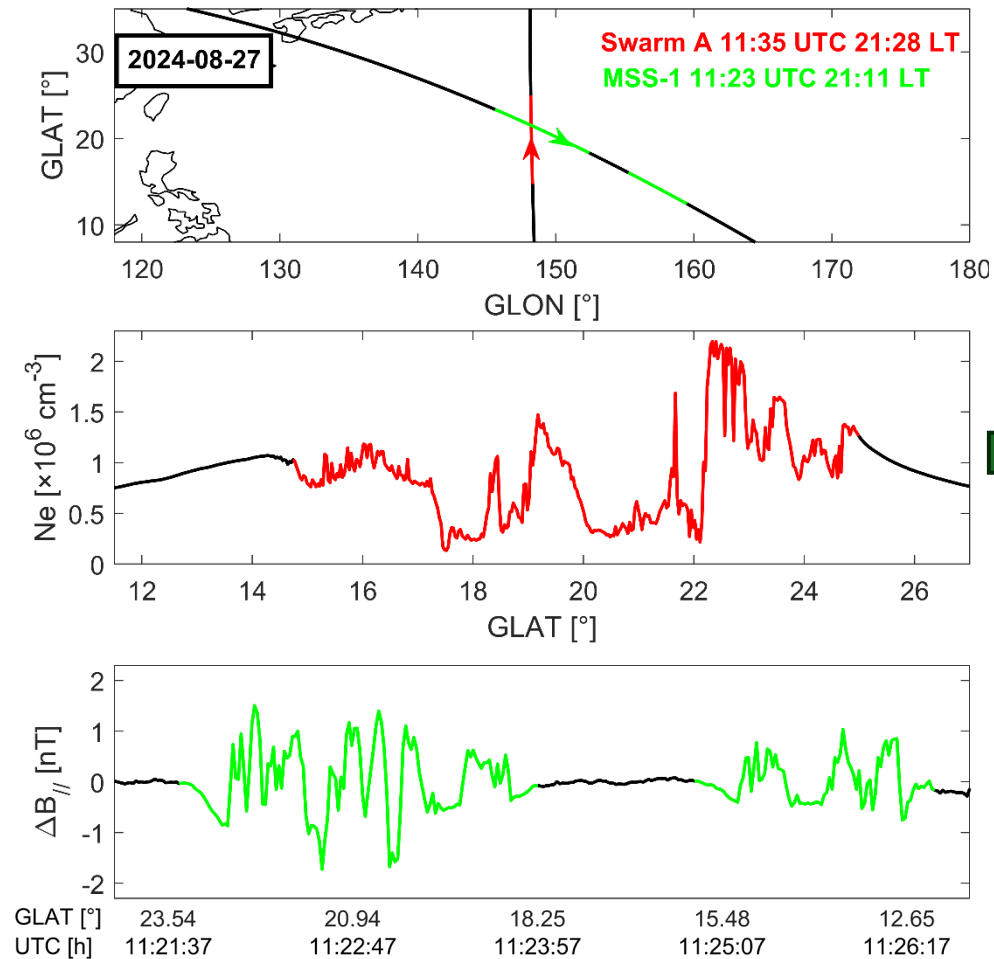
Ring current

Confirm the reliability of the MSS-1A data.

Magnetic residuals for (a) noon (11:00–13:00 MLT) and (b) midnight (23:00–01:00 MLT). The black line is the median, the dark gray shaded region is the interquartile range (25%–75%), and the light gray area denotes the 1st to 99th percentile range

No noticeable disturbances are observed in any of the three components. As solar ultraviolet radiation weakens and eventually disappears, the contribution of photoionization to the ionosphere gradually decreases, leading to a reduction in ionospheric conductivity (Prölss, 2004).

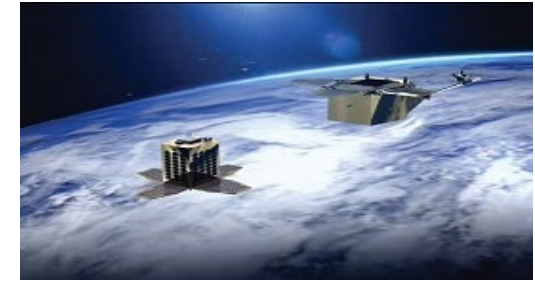
Natural signals—Equator Plasma Bubbles (EPBs)



Construct model



Application



Plasma depletion

EPBs?

MSS satellite isn't equipped with instruments for measuring electron density

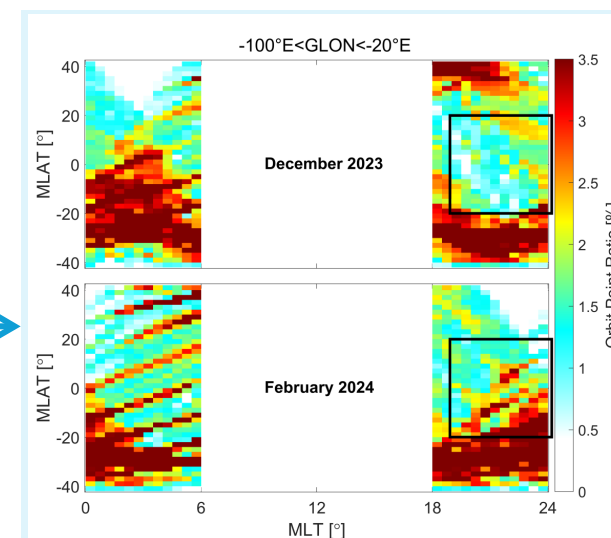
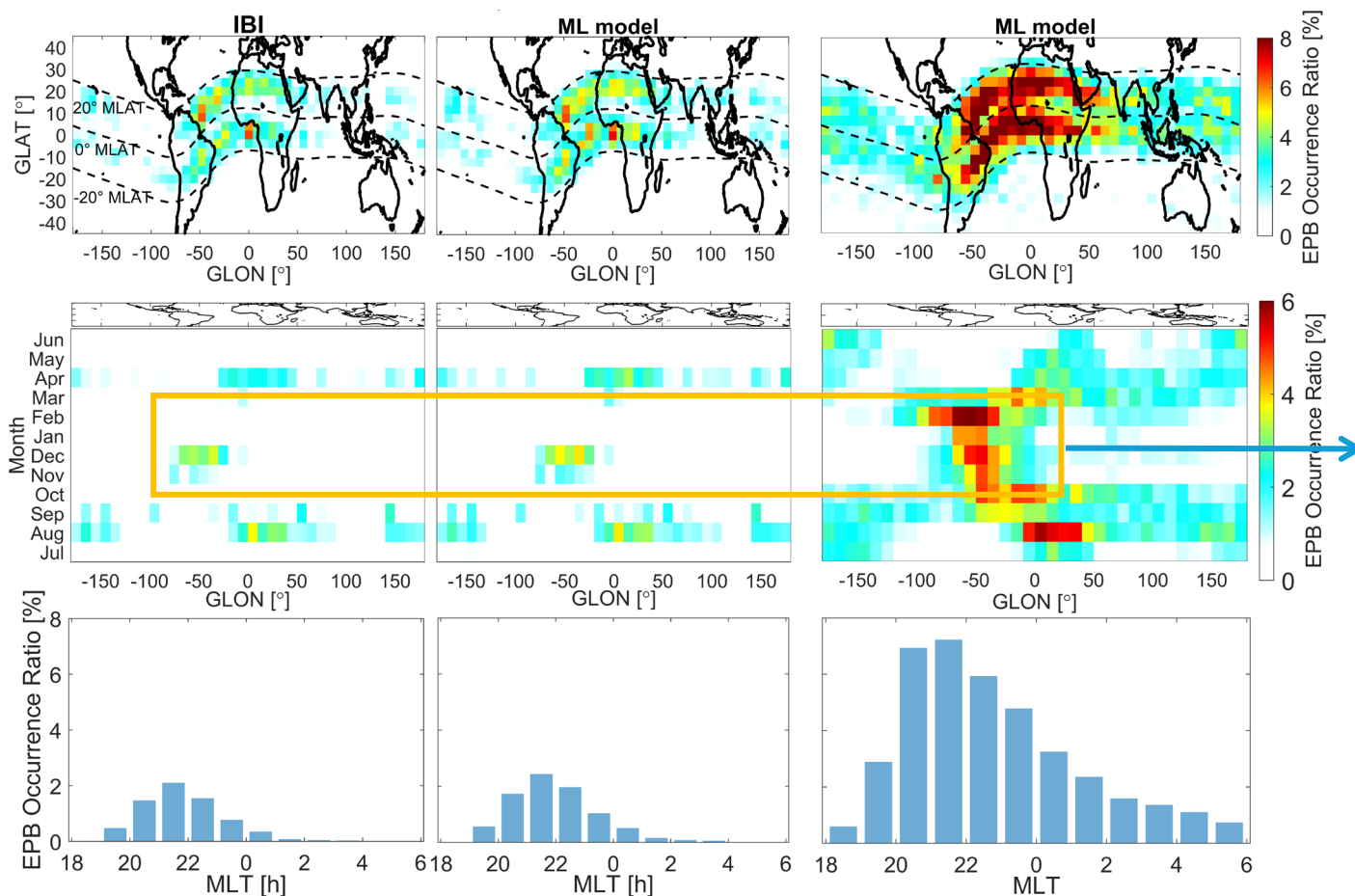
We propose an automated detection of EPBs using machine learning that based on **magnetic field data**.

Natural signals—EPBs



Swarm A

MSS-1A



Each grid reflects the **relative latitudinal** sampling coverage for each MLT.

During the EPB active period (20:00–24:00 MLT), the satellite in February predominantly sampled within $\pm 20^\circ$ MLAT, whereas in December it sampled more frequently between 20° and 40° MLAT.

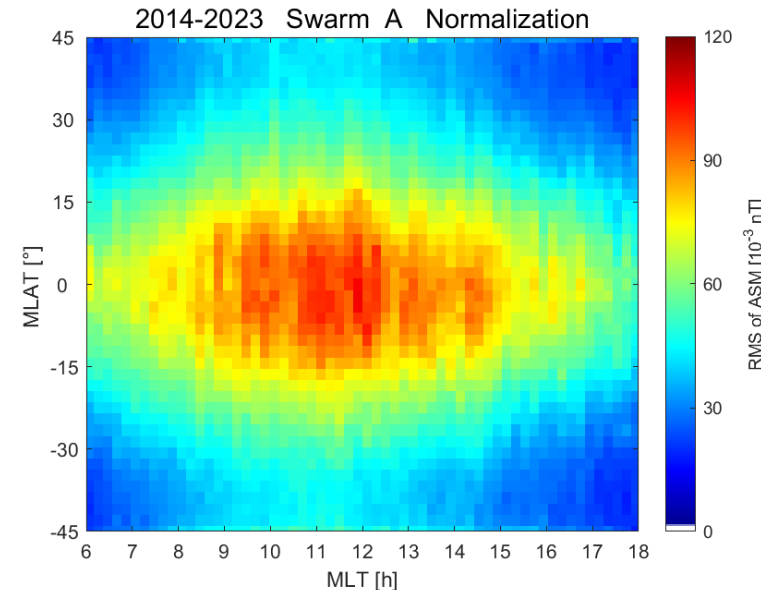
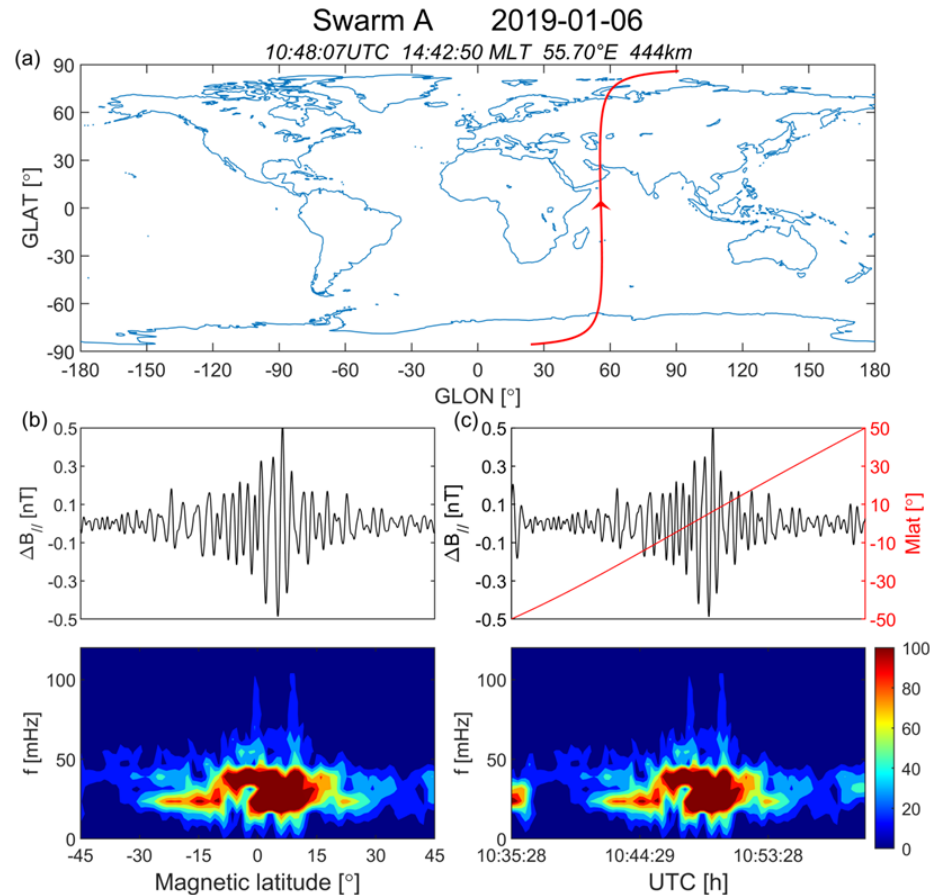
Distribution of satellite orbit point ratio in MLT and MLAT. Each MLT sector is normalized along the latitudinal profile.

EPB Occurrence distribution from Swarm A (IBI/ML) and MSS-1 (ML) under $K_p < 3$, 18:00–06:00 MLT

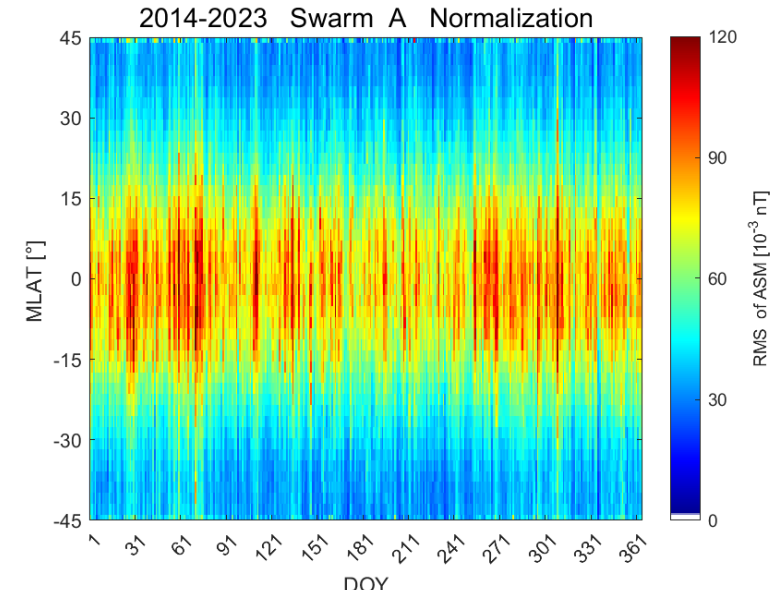
Natural signals—Upstream waves



Mlat-MLT



Mlat-DOY

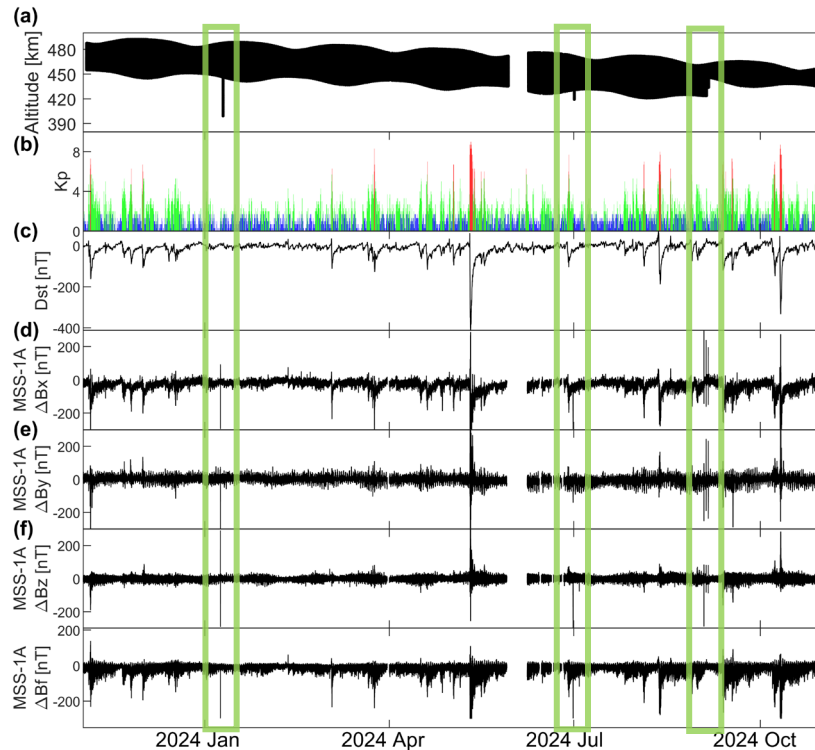


- The distribution presents a nearly elliptical structure, similar to the shape of eye. The amplitude gradually decays from the center outward. The distribution showed good north-south symmetry.
- The maximum amplitude is mainly concentrated near noon in magnetic time, and the fluctuation intensity between 10 and 12 o'clock is the most significant.
- The right figure shows two significant peaks and one valley. The minimum value located near the summer solstice .

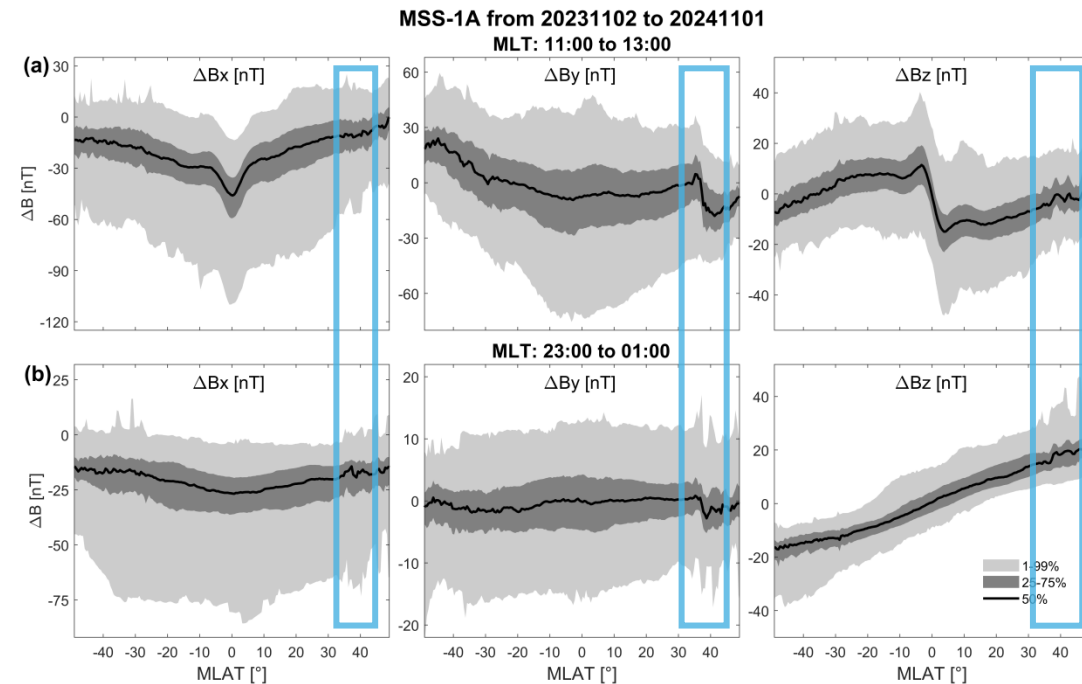
Artificial signals



Although magnetometers undergo rigorous testing and calibration before launch, their accuracy can still be affected by variations in onboard electrical and electronic systems after deployment.

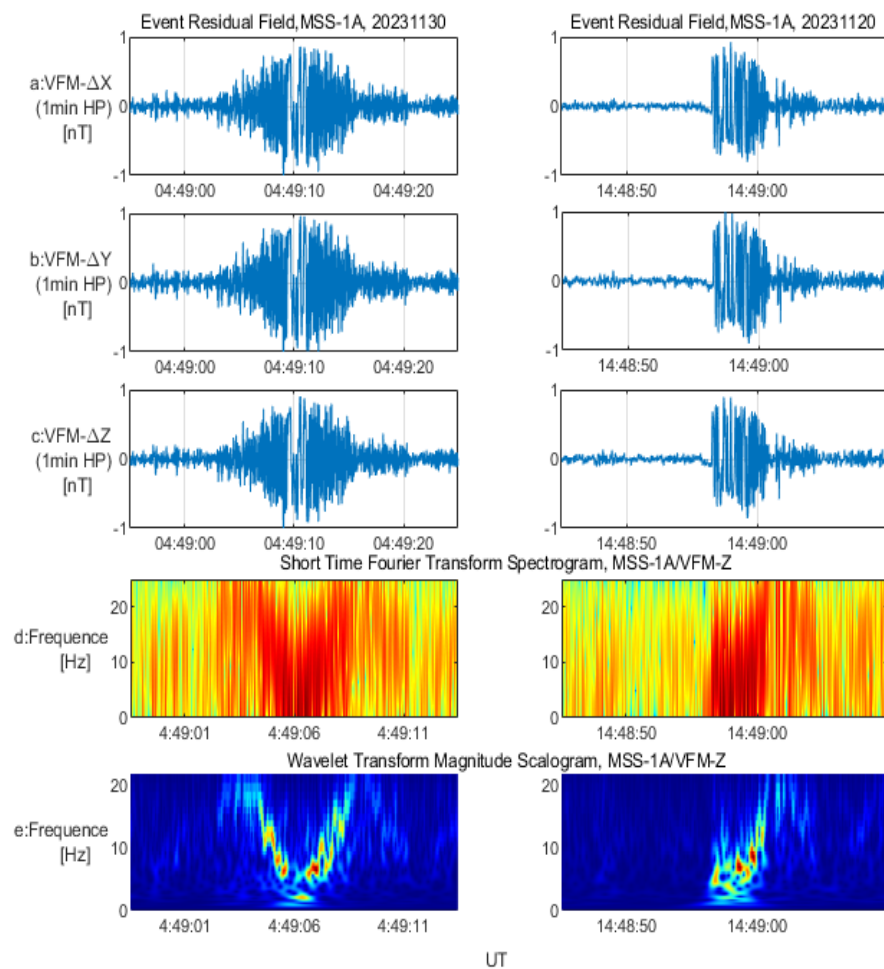


The disturbances caused by **altitude and orbit control** of the satellite, with the clear spike of magnetic disturbance exceeding 300 nT.

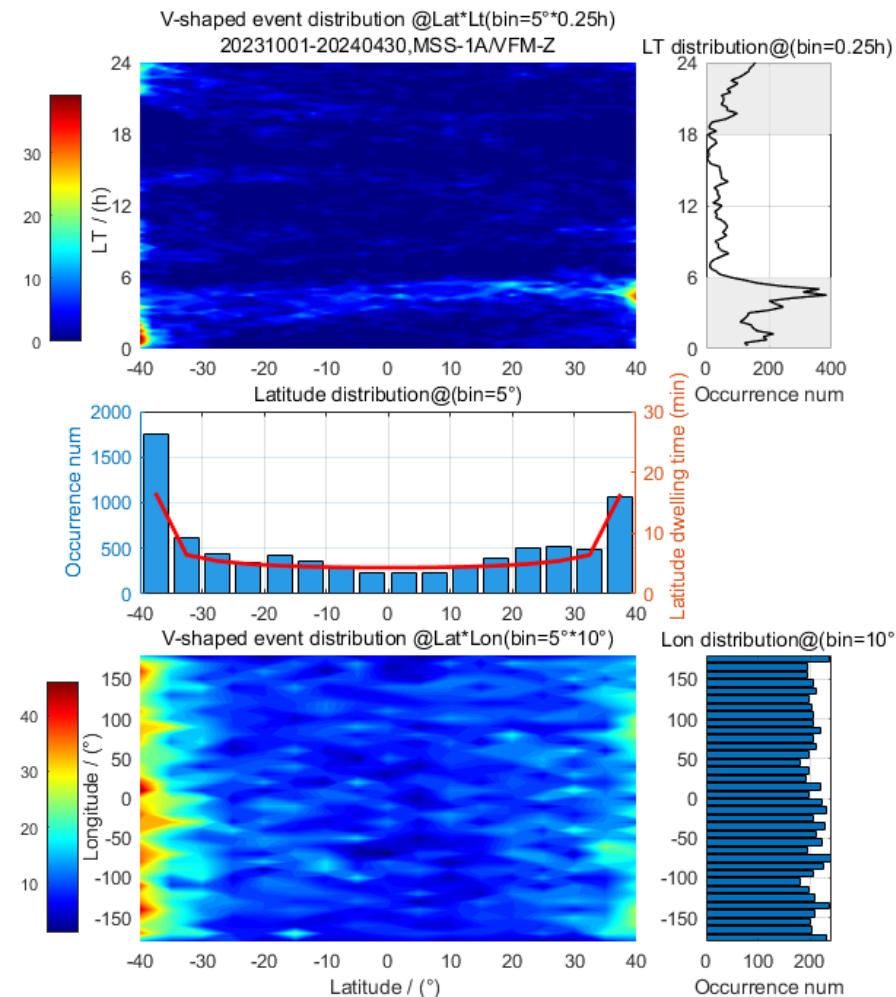


Disturbances of unknown origin. All six subplots show a noticeable drop at 37°N MLAT with a magnitude of 2 nT, along with high-frequency perturbations at 35°–50°N MLAT.

Artificial signals



Left: An example of a V-shaped event.
Right: An example of an incomplete V-shaped event.



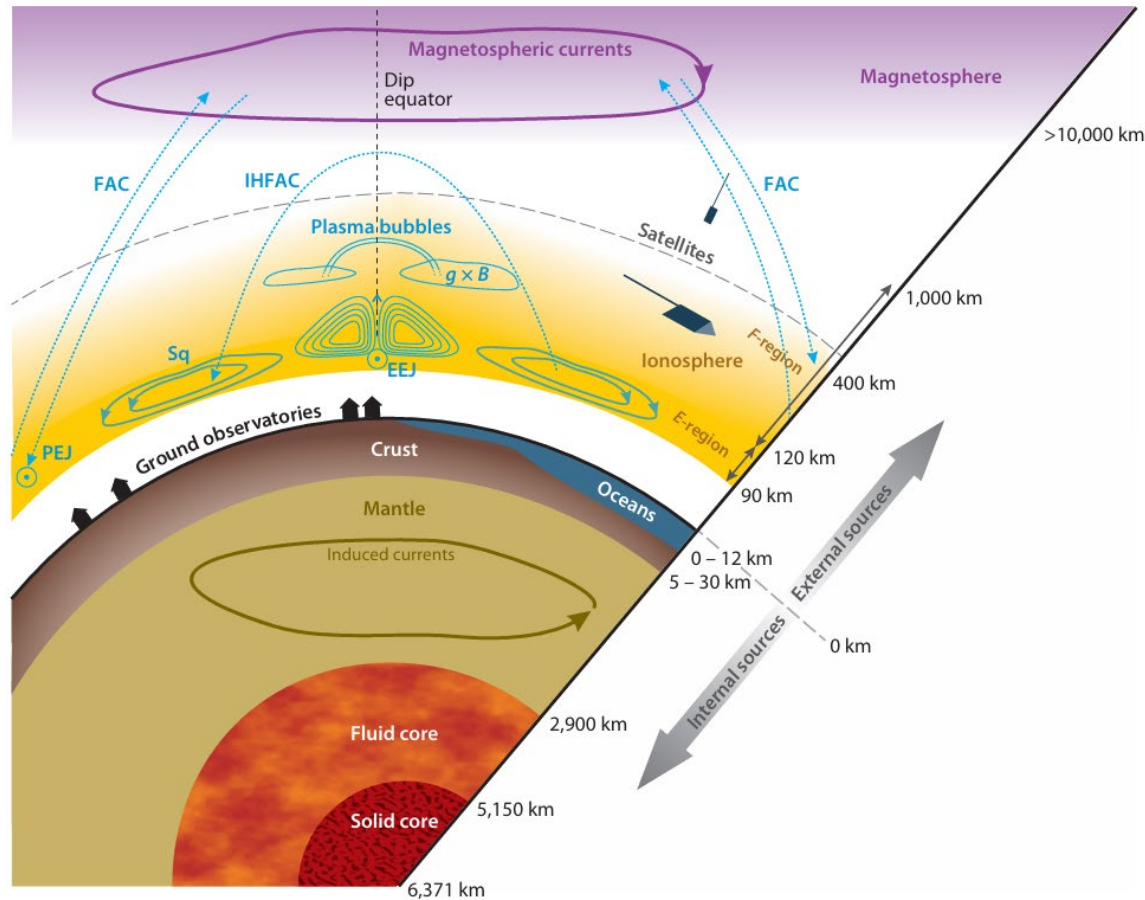
Statistics relating observed V-shaped events to the local time and the latitude and longitude of MSS-1A at the time of each observation.

(Song et al., 2025, EPP)



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Space magnetic field and currents

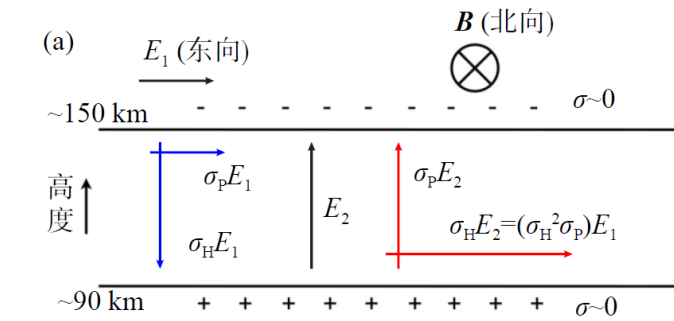


Ionospheric currents	Magnetic effect [nT]
Sq	30~250
EEJ	10~150
IHFAC	0~40
PEJ	0~1500
夜侧水平纬向电流	0~10
重力和压力梯度电流	5~10
抗磁电流	0~0.5

(Olsen and Stolle, 2012; Xiong et al., 2024)

- The Space currents can effectively reveal the coupling processes between the magnetosphere, ionosphere, and neutral atmosphere.
- How to accurately characterize the magnetic field variations induced by spatial currents remains an unresolved issue in existing geomagnetic field models.

Calculating the equatorial electrojet (EEJ)

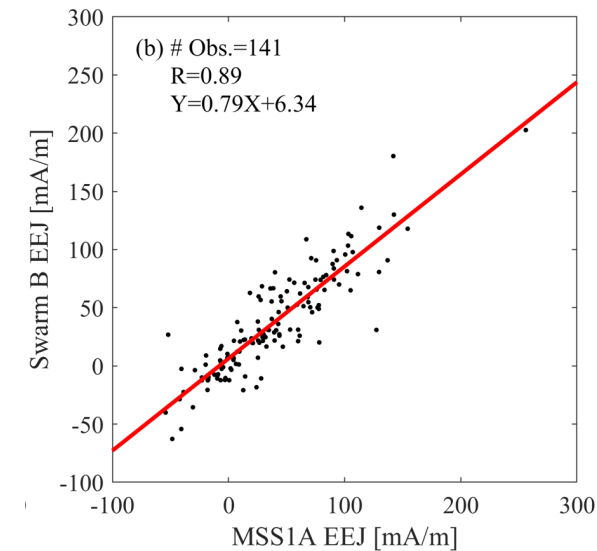
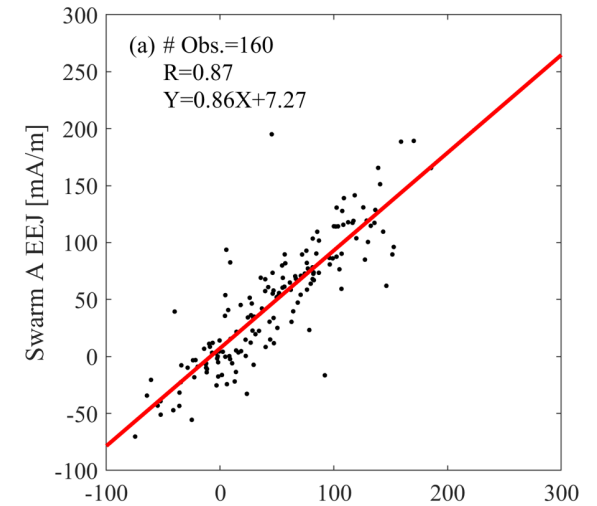
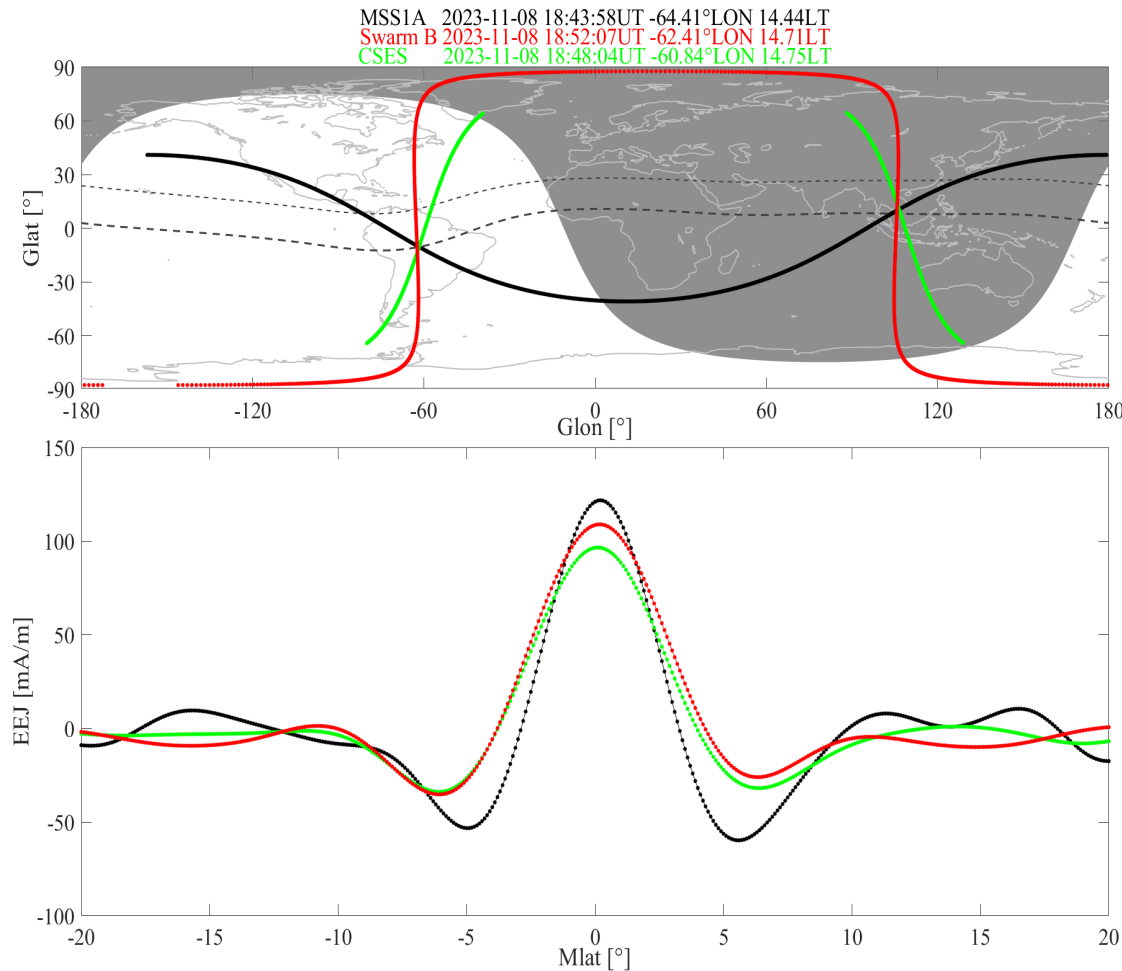


(b)

Diagram illustrating the geometry of the Earth's magnetic field and the EEJ current density. The Earth's surface is shown as a curved line with points S and N . The magnetic field vector B is shown at an angle $\Delta\beta(i, j)$ to the vertical. The current density vector J is shown at an angle $\Delta\beta(i, j)$ to the vertical. The distance from the center of the Earth to the point i is R_{cur} . The distance from the point i to the point j is Δh . The EEJ current density is shown as a vector EEJ .

$$\Delta B_x(i, j) = -\frac{\mu_0 I}{2\pi} \cdot J(j) \cdot \Delta l \cdot \frac{h(i, j)}{x^2(i, j) + h^2(i, j)}$$

$$\Delta B_z(i, j) = \frac{\mu_0 I}{2\pi} \cdot J(j) \cdot \Delta l \cdot \frac{x(i, j)}{x^2(i, j) + h^2(i, j)}$$



(Lühr et al., 2003; Xiong et al., 2024; Huang et al., 2024)

The inversion of Solar quiet (Sq) currents



The residual magnetic field can be expressed as:

$$X = \frac{\partial V}{r \partial \theta} = \sum_{n=1}^{\infty} \sum_{m=0}^n n \left(\frac{r}{a}\right)^{n-1} [g_n^m \cos m\lambda + h_n^m \sin m\lambda] \frac{\partial P_n^m(\cos \theta)}{\partial \theta}$$

$$Y = -\frac{1}{r \sin \theta} \frac{\partial V}{\partial \lambda} = \sum_{n=1}^{\infty} \sum_{m=0}^n n \left(\frac{r}{a}\right)^{n-1} [g_n^m \sin m\lambda - h_n^m \cos m\lambda] \frac{m P_n^m(\cos \theta)}{\sin \theta}$$

$$Z = \frac{\partial V}{\partial r} = - \sum_{n=1}^{\infty} \sum_{m=0}^n n \left(\frac{r}{a}\right)^n [g_n^m \cos m\lambda + h_n^m \sin m\lambda] P_n^m(\cos \theta)$$

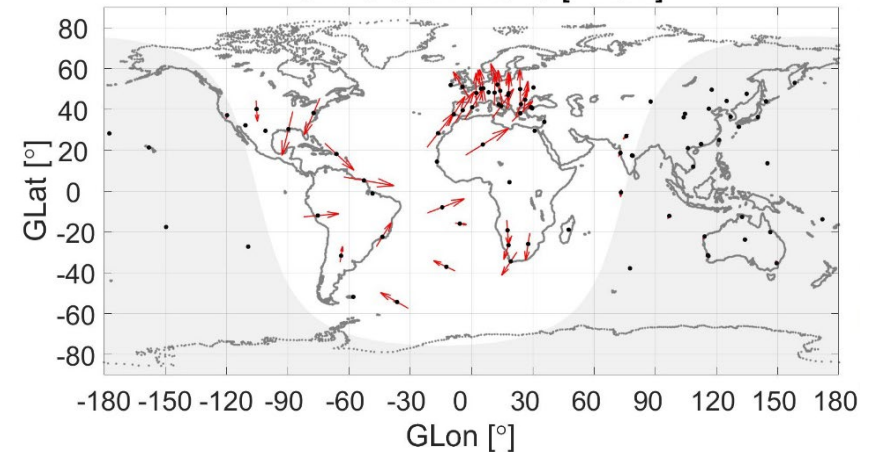
The equivalent current can be expressed as :

$$J^{ex} = -\frac{1}{\mu_0} \frac{2n+1}{n+1} V^{ex}$$

$$J^{in} = \frac{1}{\mu_0} \frac{2n+1}{n} V^{in}$$

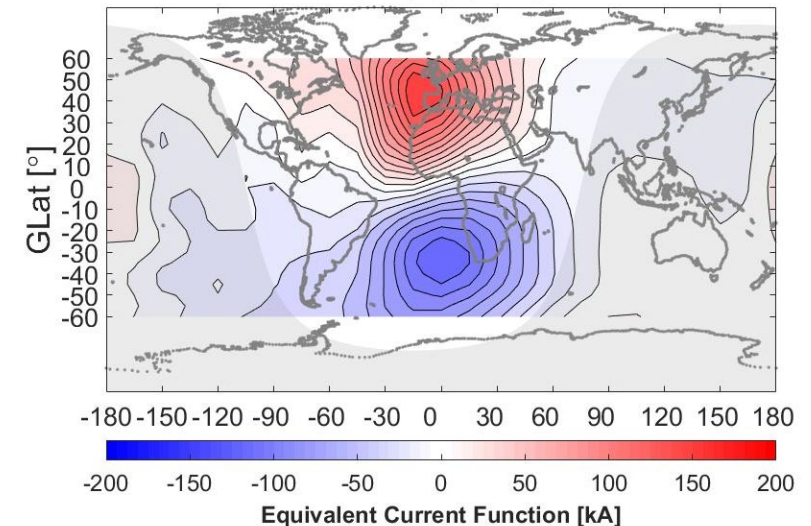
Current vector

2024-5-9 UT=13 J [mA/m]



Inversion results

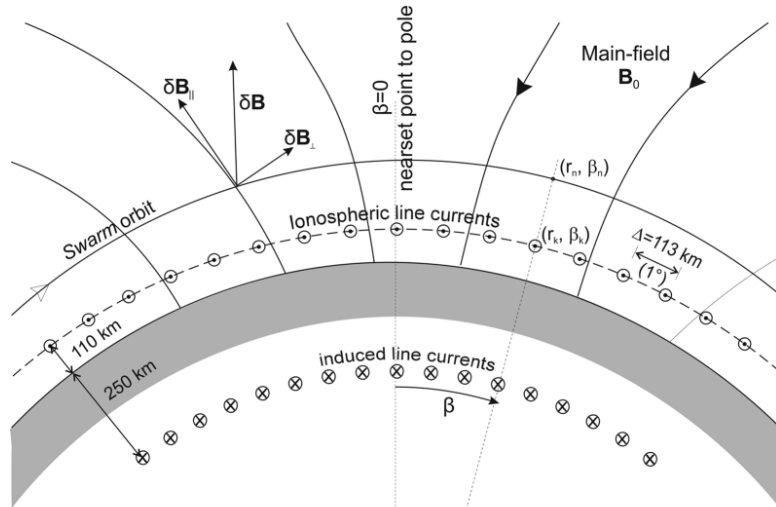
2024-5-9 UT=13



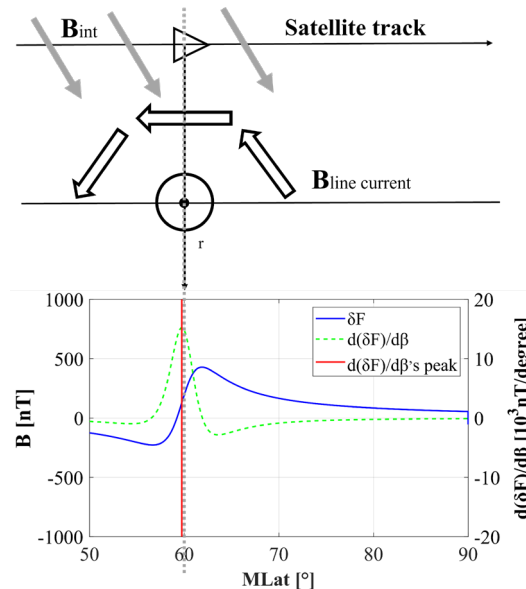
Calculating the Auroral electrojet (AEJ)



Calculate Method of AEJ



(Aakjær et al., 2016)

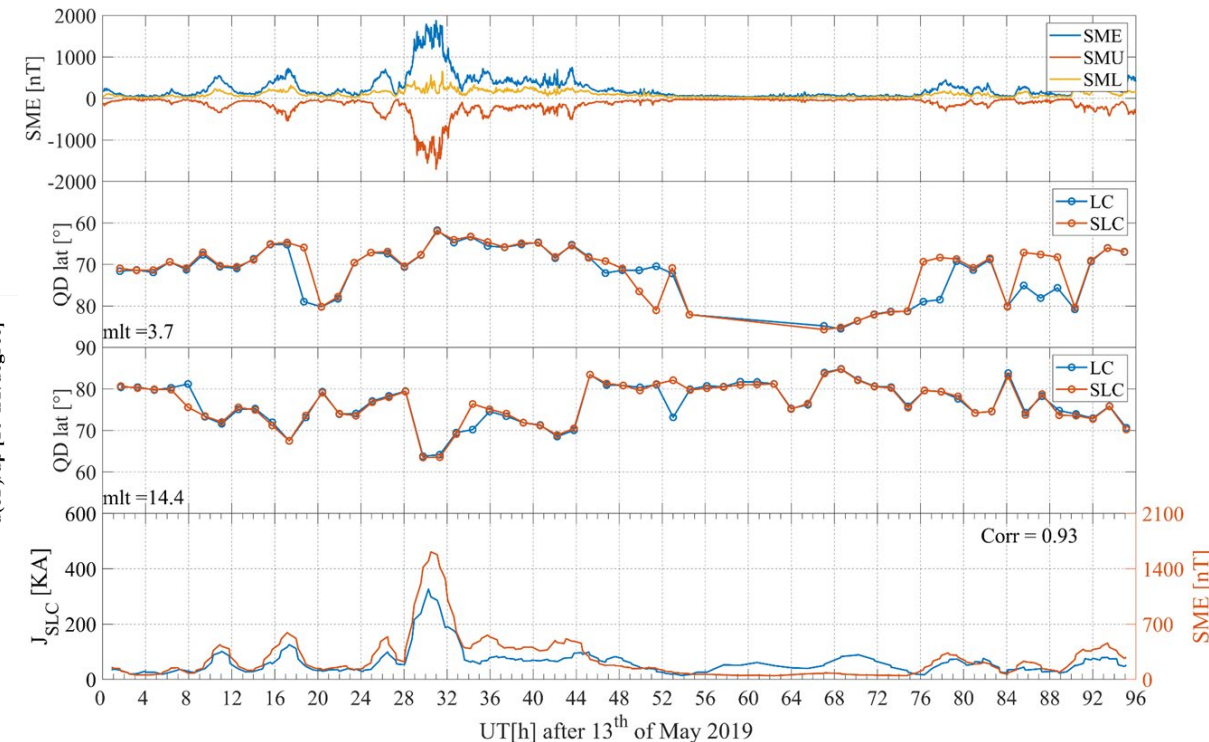


$$j^{L_2} = (G^T G + \alpha^2 I)^{-1} G^T \delta F \longrightarrow j = \frac{2\pi(r_n - r_k)^2}{r_k \mu_0 \sin I} \frac{d\delta F_n}{d\beta}$$

Line Current
(Olsen, 1996)

Single Line Current
(Vennerstrom and Moretto,
2013 ;Qian et al., 2025)

Compare with Swarm AEBS Products (AEJ by LC method) and SME Index

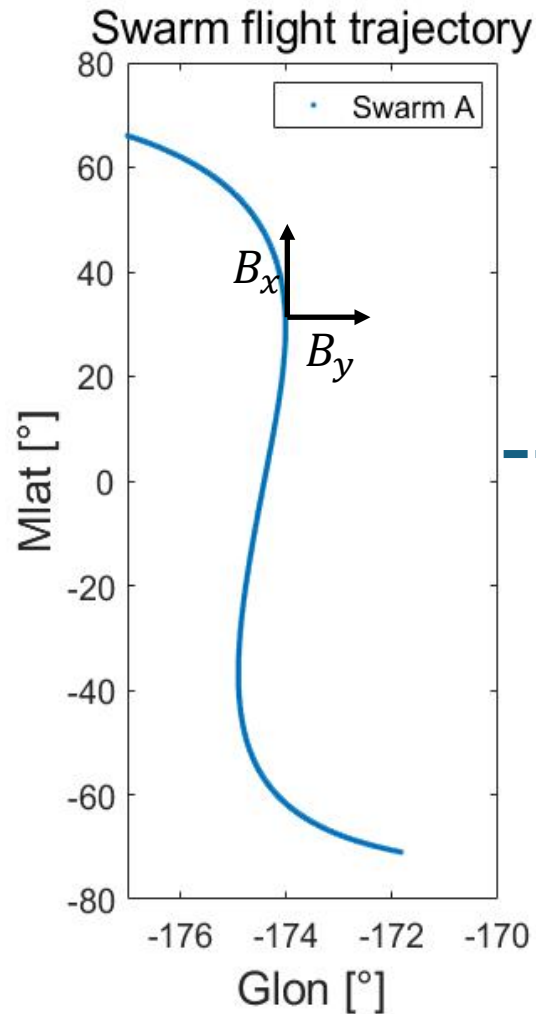


- Comparison Between SLC and LC Methods
- Latitudinal Dynamics of AEJ calculate by SLC

The inversion of Field-Aligned Current (FAC)



Single-satellite



The traditional form of Ampère's law, the curl-**B** relation, was employed to calculate the vertical current density,

$$j_z = \frac{1}{\mu_0} \left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right] \quad (1)$$

With only one satellite, the equation can be reduced to

$$j_z = \frac{1}{\mu_0} \frac{1}{v_x} \frac{\partial B_y}{\partial t} \quad (2)$$

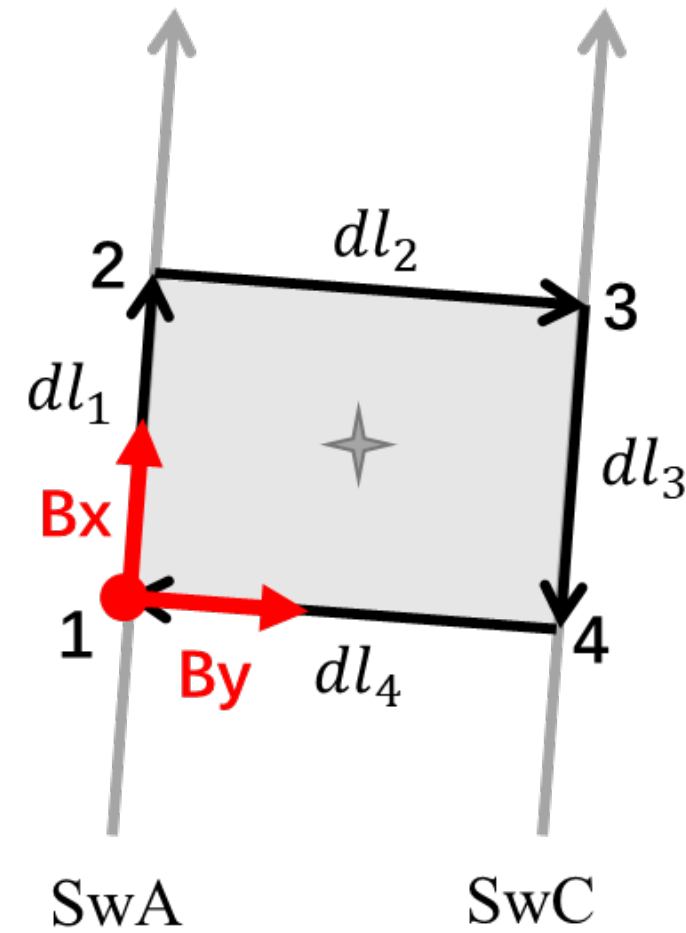
The vertical current density estimates are derived by applying Ampère's ring integral:

$$j_z = \frac{1}{\mu_0 A} \oint \mathbf{B} \cdot d\mathbf{l} \quad (1)$$

In the practical calculation, the discrete form is used

$$j_z = \frac{1}{2\mu_0 A} [(B_{x1} + B_{x2})dl_1 + (B_{y2} + B_{y3})dl_2 - (B_{x3} + B_{x4})dl_3 - [(B_{y4} + B_{y1})dl_4] \quad (2)$$

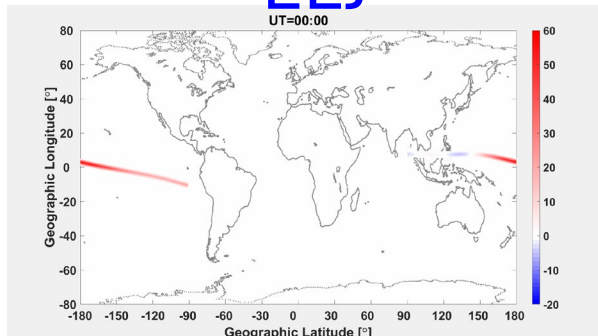
Dual-satellite



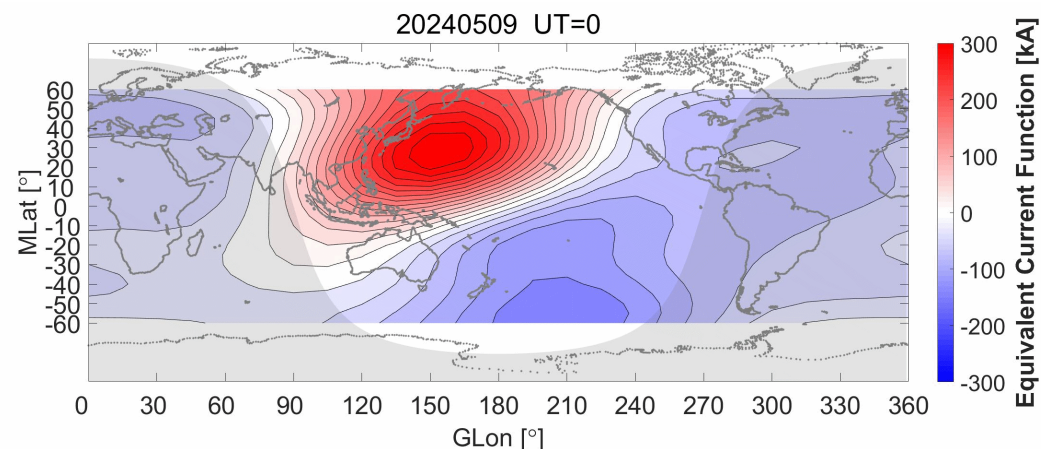
Modelling ionospheric currents



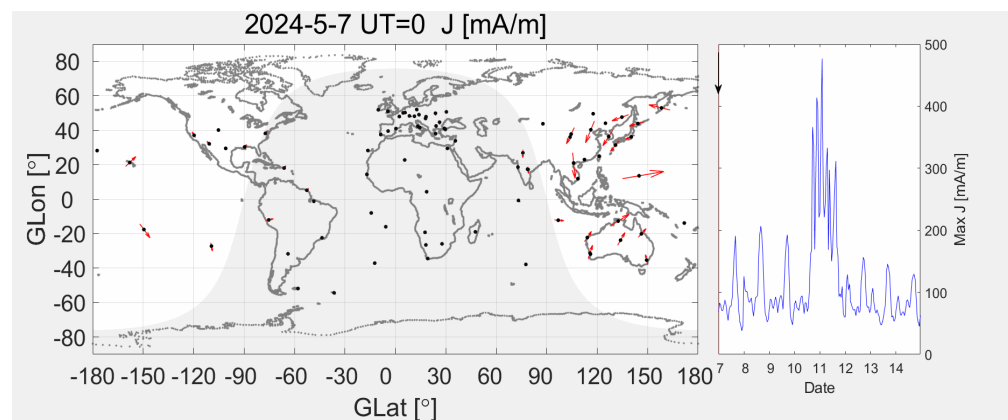
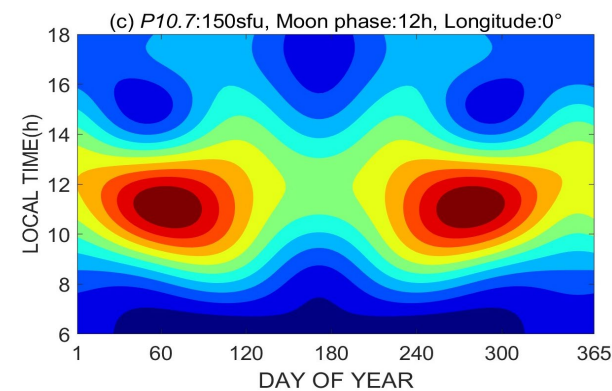
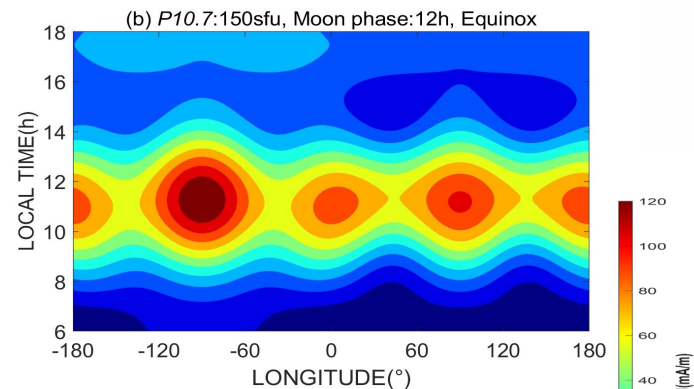
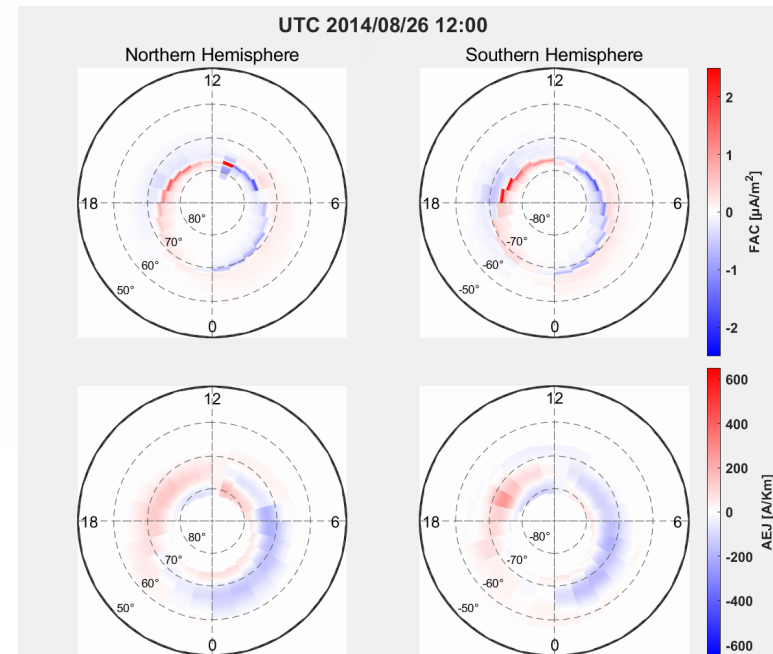
EEJ



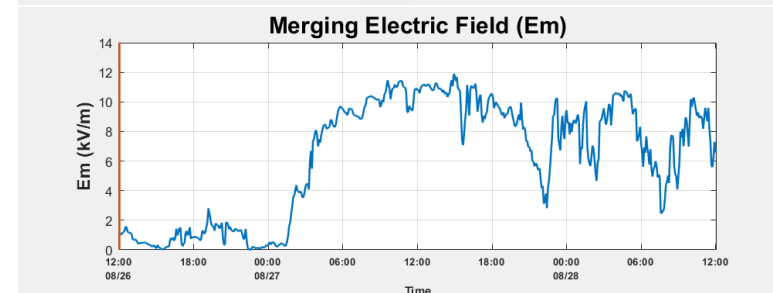
Sq



FAC and PEJ



(Wen et al., 2023; Sun et al., 2025, in preparation)



Modelling magnetic field



IGRF-14: Call for Candidate Models

Date: 05-Mar-2024; Version: 1; Authors: Ciaran Beggan and Clemens Kloss

Dear modellers and evaluators,

Please consider contributing to the 14th generation International Geomagnetic Reference Field (IGRF-14). We seek candidate models for the following products:

- 1) Internal field (main field) for 2025.0 to spherical harmonic (SH) degree and order 13.
- 2) Predicted average secular variation for 2025.0-2030.0 to SH degree and order 8
- 3) Internal field (main field) for 2020.0 to SH degree and order 13

The requested numerical resolution of the coefficients is 0.01 nT for all products. This will allow calculation of the final models to a resolution of 0.1 nT for IGRF-2025 and SV-2025-2030 and 0.01 nT for DGRF-2020.

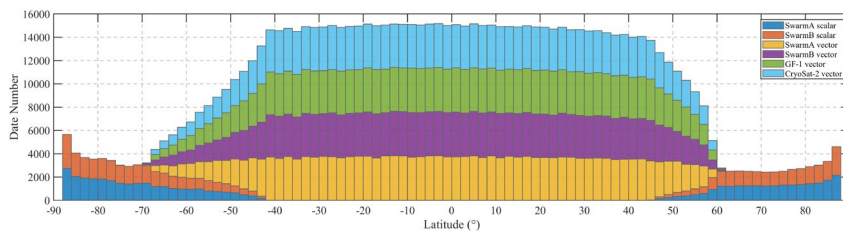
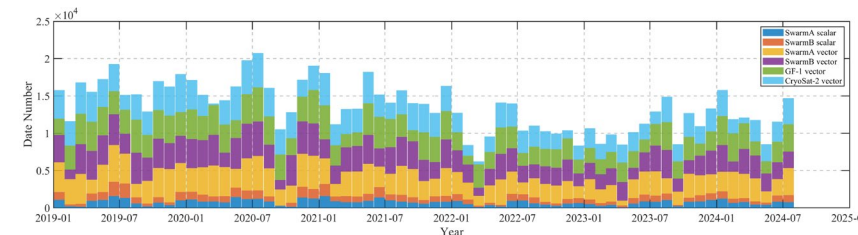
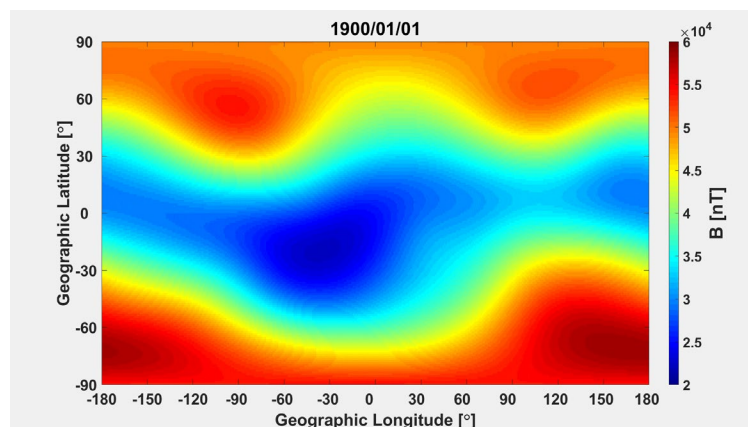
Each team that plans to submit candidate models is requested to provide a list of the products they intend to submit and a description of their methodology by 1st June 2024. Each team should also prepare a more extensive description of their product for the time of their submission, 1st October 2024, that will help with the evaluation of the IGRF candidate models. The intention is to finalise the models by late November and release them by mid-December.

Further details are given below. We thank you for your contributions.

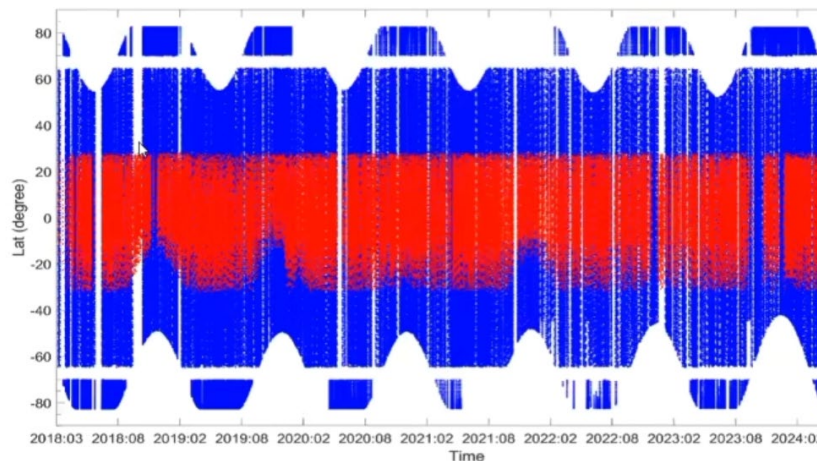
Regards,

Ciaran Beggan (ciar@bgs.ac.uk) and Clemens Kloss (ancklo@space.dtu.dk)

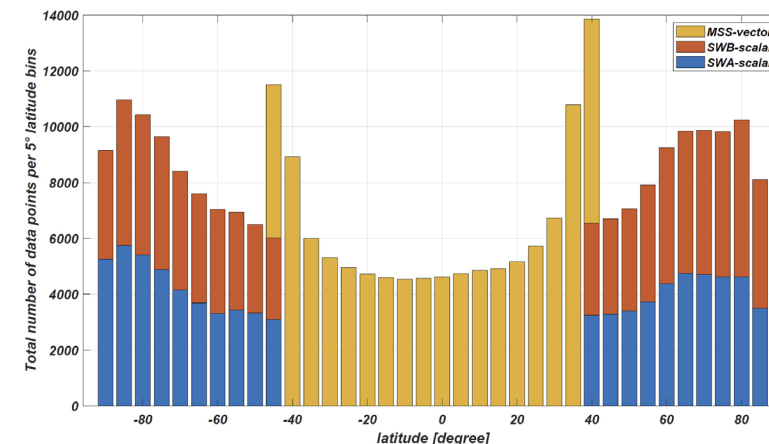
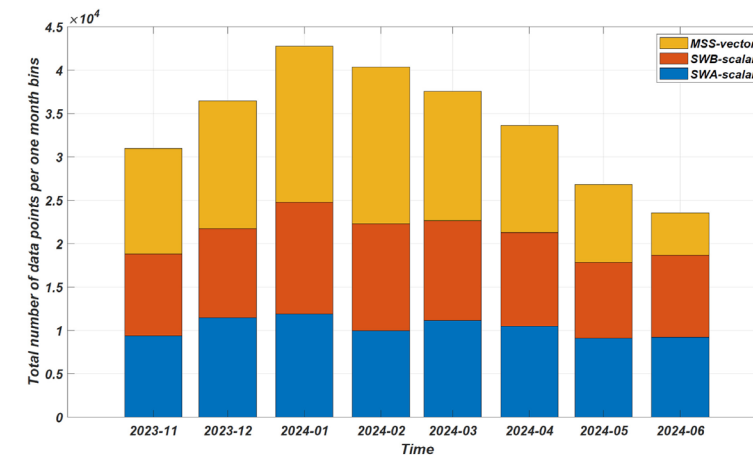
The variation of Earth's magnetic field



WHUEMM BY WHU:
SwarmA+B+CryoSat+GRACE-FO



CGGM by NINH:CSES

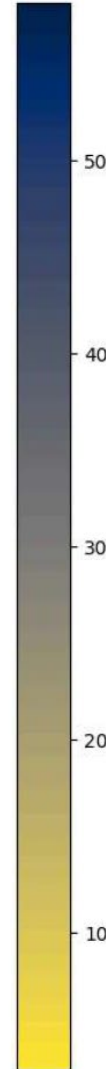
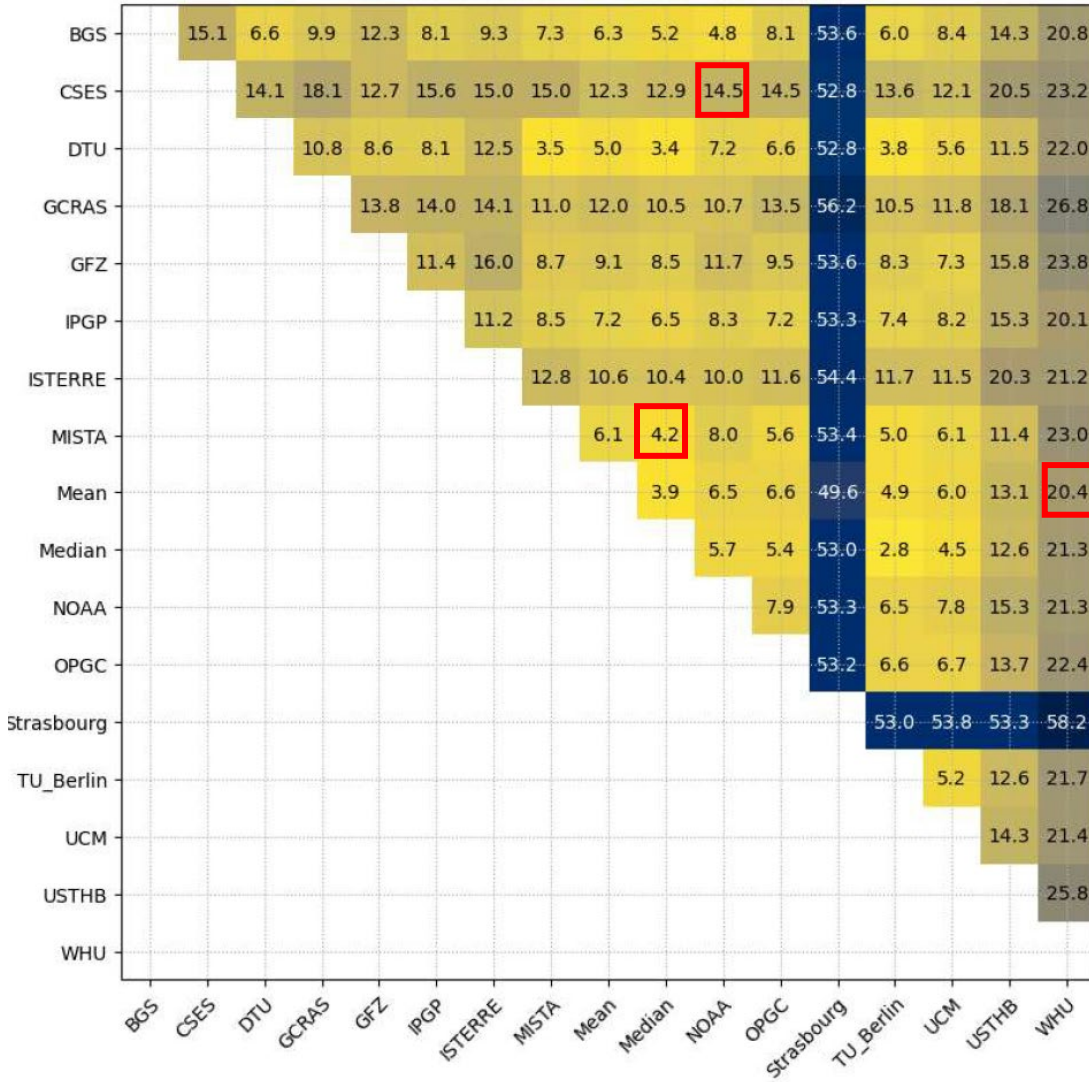


MIMF by MISTA:SwarmA+B+MSS-1

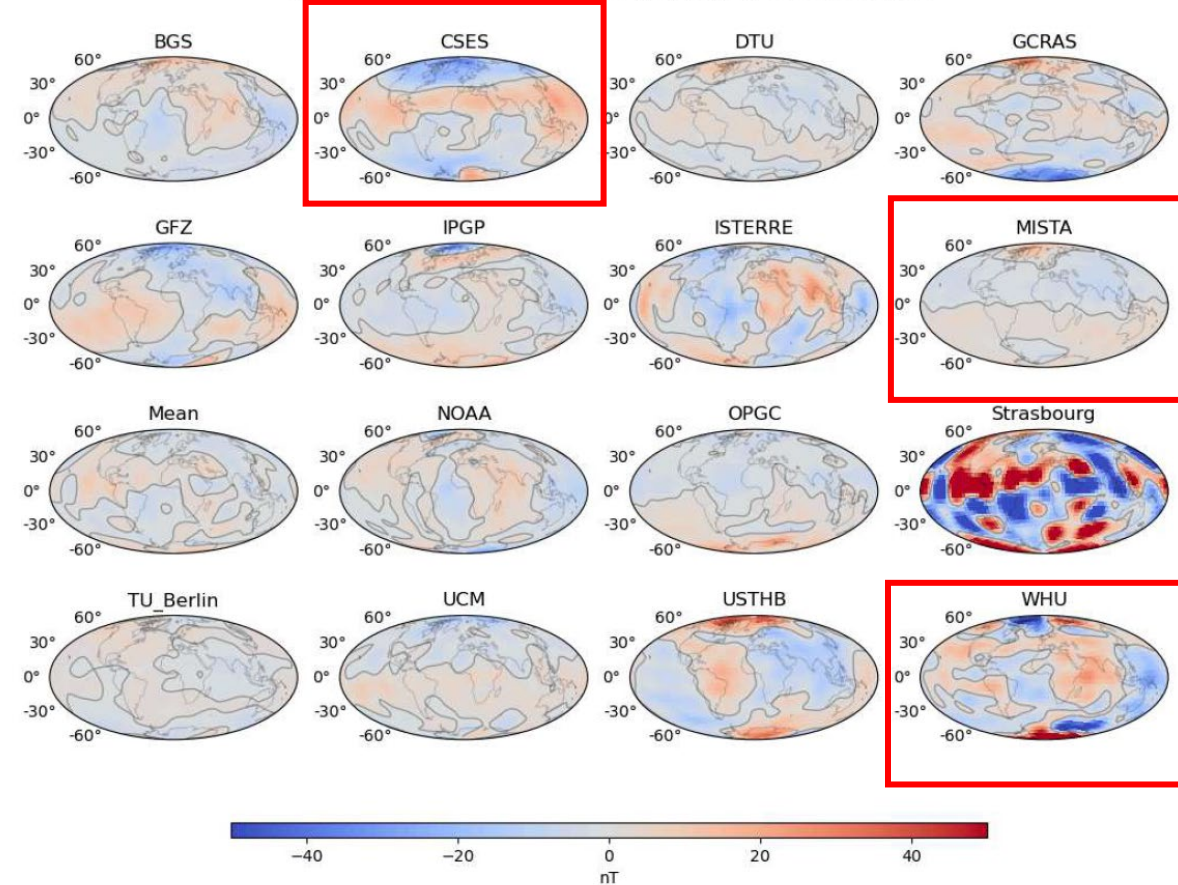
Modelling magnetic field



RMS Difference between IGRF 2025 candidates



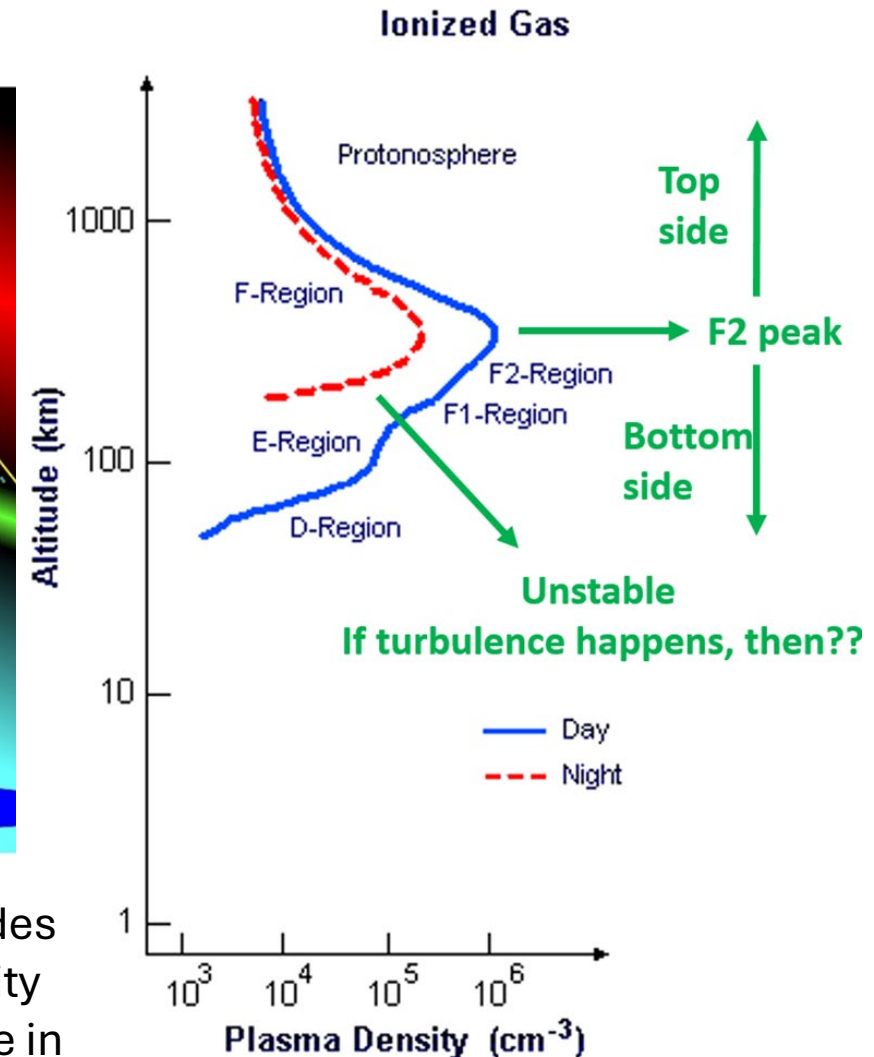
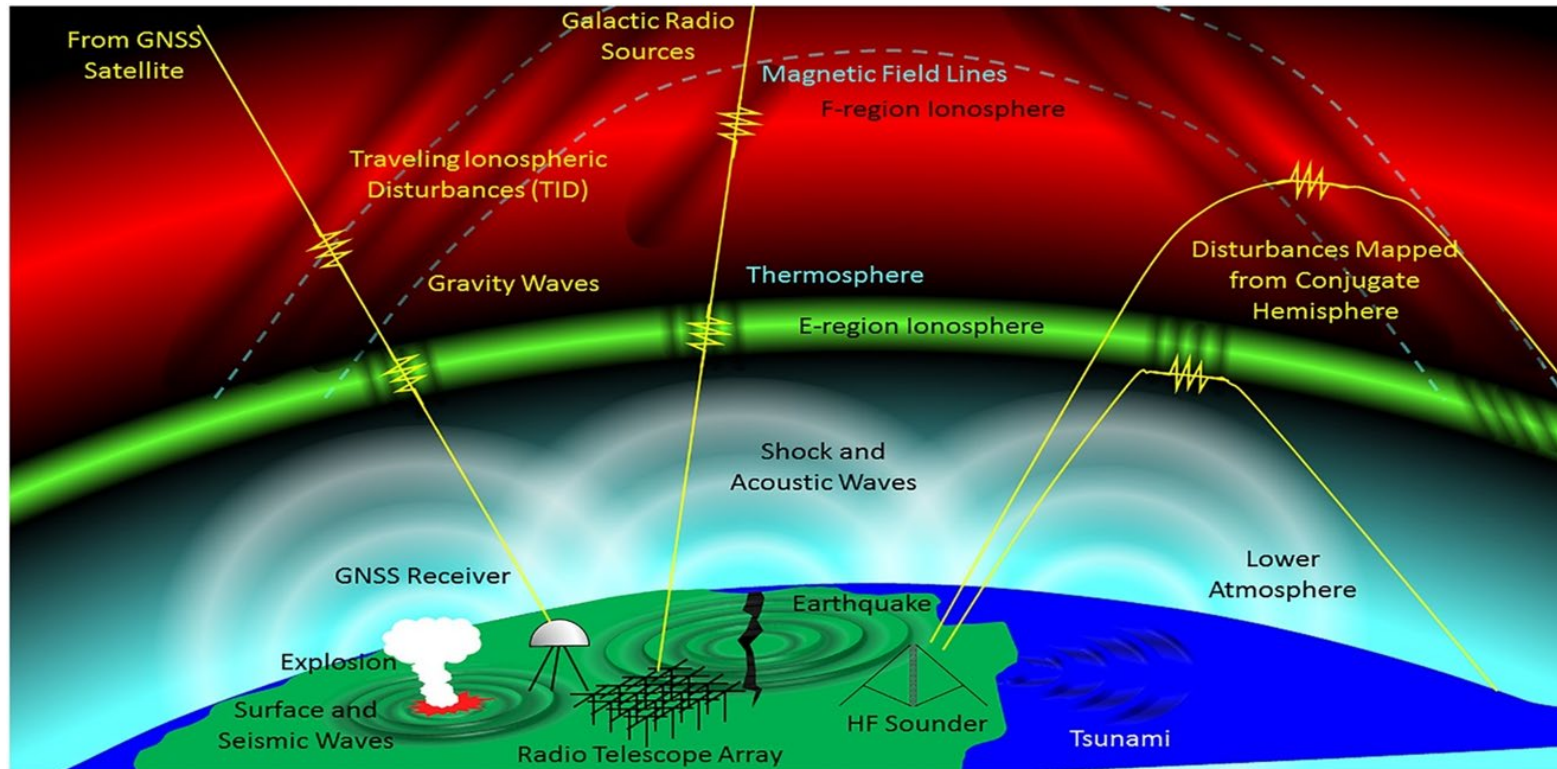
Difference in B_r between Candidate Median / IGRF 2025 candidates



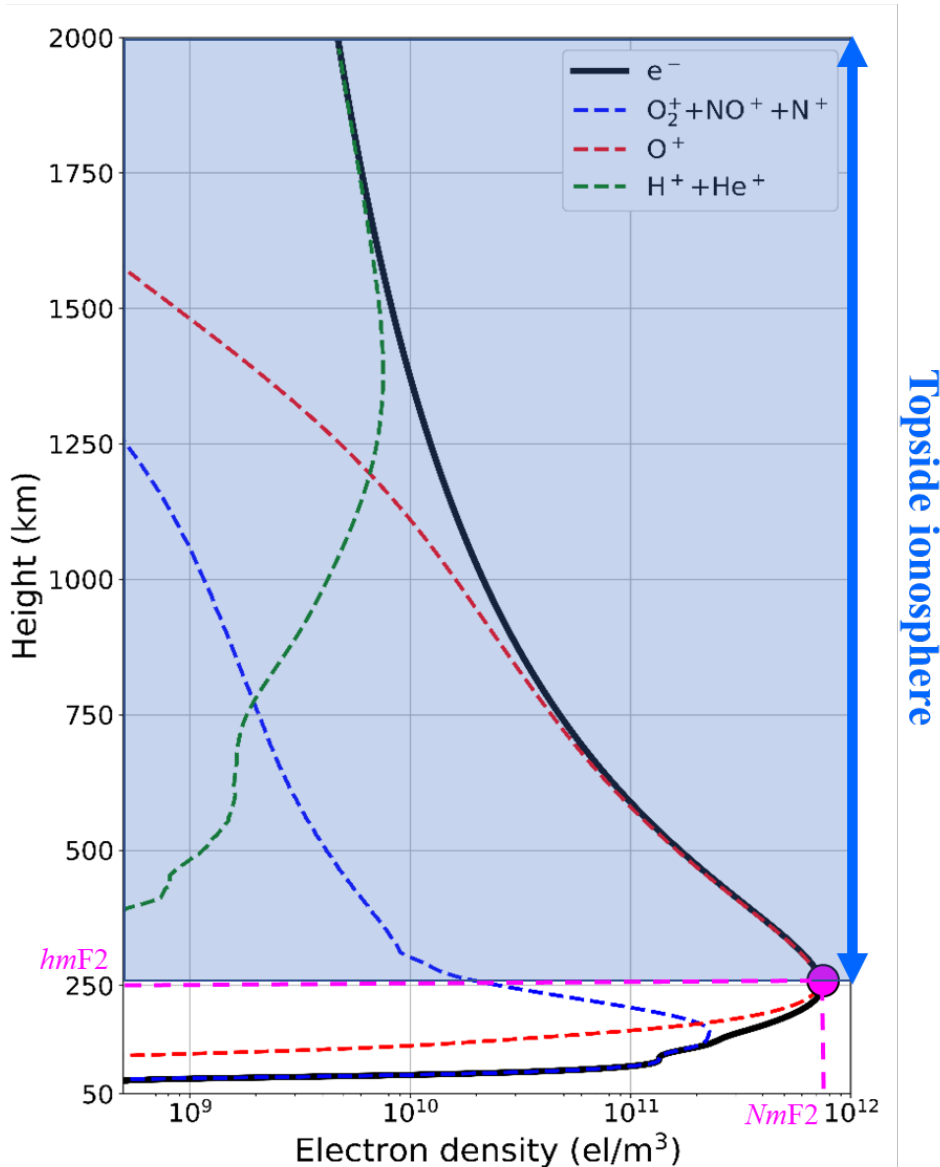


- **The project's objectives**
- **The data utilised to achieve the project's objectives**
- **Progress of the project in the last year**
 - **Analysis of satellite magnetic data**
 - **Ionospheric current inversion and modeling**
 - **3D ionospheric modeling**
- **List of Publications**

The Earth's ionosphere



The Earth's ionosphere is a partially ionized region of the atmosphere at altitudes ranging from 60 km to 1000 km. The spatiotemporal variation of electron density in the ionosphere is rapid, and because the ionosphere plays an important role in communication and satellite navigation, it is necessary to establish an accurate ionospheric model.



Introduction and motivation

The **topside ionosphere** is the region extending from the F2-layer peak (*NmF2*, *hmF2*) to the overlying plasmasphere:

- monotonic decrease of the electron density;
- diffusion of plasma along geomagnetic field lines;
- is the environment where LEO satellites fly;
- gives the largest contribution to the total electron content;
- is a region difficult to probe and then modeling.

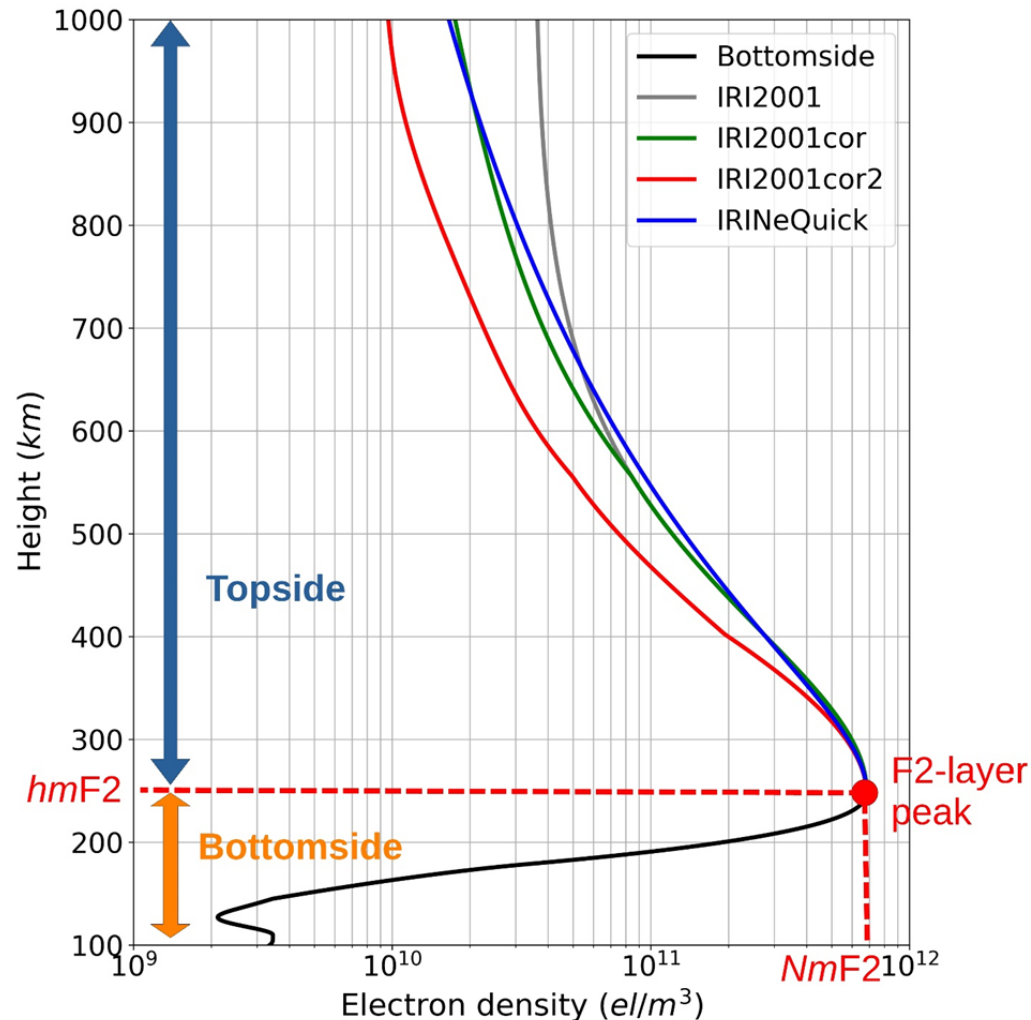
The last version of the **International Reference Ionosphere (IRI-2020**, Bilitza et al. 2022) describes the topside ionosphere through four different options.

Goal: Validation of the IRI-2020 topside options against electron density topside profiles from COSMIC-1 & -2 GNSS radio occultation.

Validation of the IRI-2020 topside ionosphere options



Year 2008 Day 216 hour(UT) 5.655 latgeo(°) 27.53 longeo(°) -151.86 foF2(MHz) 7.425 hmF2(km) 249.0



IRI-2020 topside ionosphere options

- IRI2001 (Bent et al. 1972; Rawer et al. 1978)

$$N_e(h) = NmF2 \cdot \exp\left[-\frac{B(x)}{\alpha}\right]$$

- IRI2001cor (Bilitza 2004)

$$N_e(h) = NmF2 \cdot \exp\left[\frac{-B(x)}{\alpha} + TCOR(h, \text{modip}, \text{day/night})\right]$$

- IRI2001cor2 (Bilitza and Xiong 2021)

$$N_e(h) = NmF2 \cdot \exp\left[\frac{-B(x)}{\alpha} + TCOR(h, \text{modip}, \text{day/night}) + SCOR(PF10.7)\right]$$

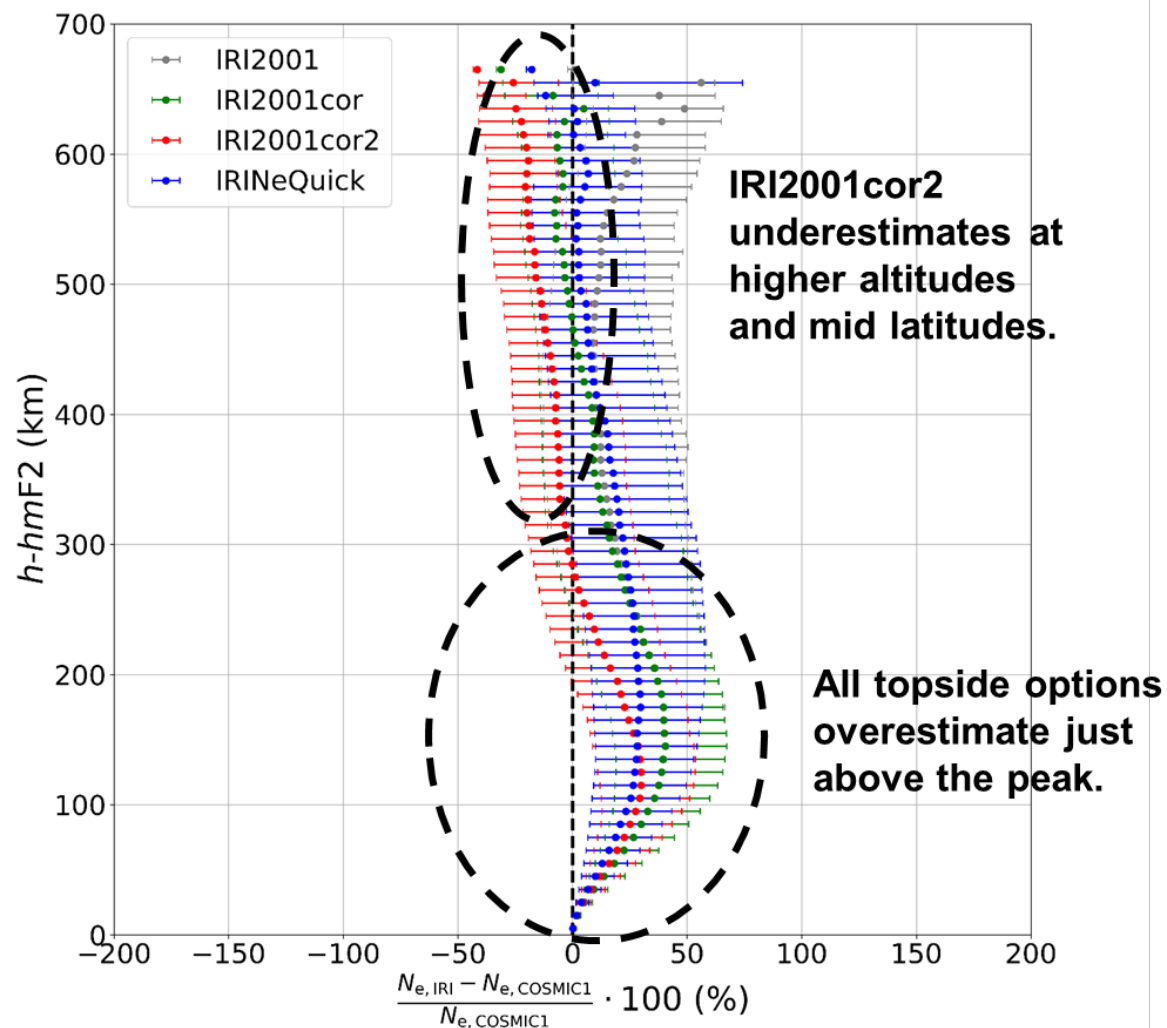
- IRI2001cor2 (Nava et al. 2008)

$$N_e(h) = 4NmF2 \frac{\exp\left(\frac{h - hmF2}{H}\right)}{\left[1 + \exp\left(\frac{h - hmF2}{H}\right)\right]^2}$$

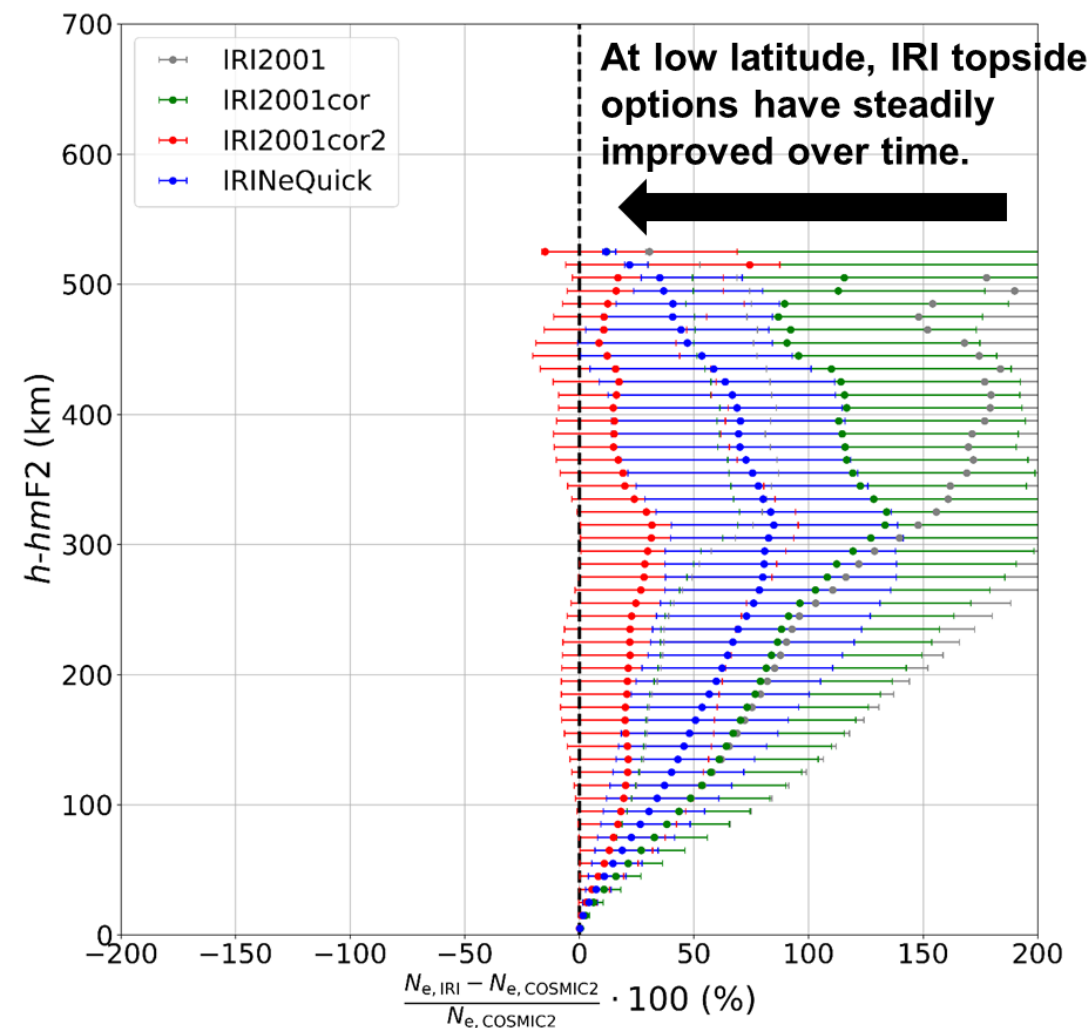
Validation of the IRI-2020 topside ionosphere options



**Topside electron density percentage residuals
IRI options vs COSMIC1**



**Topside electron density percentage residuals
IRI options vs COSMIC2**

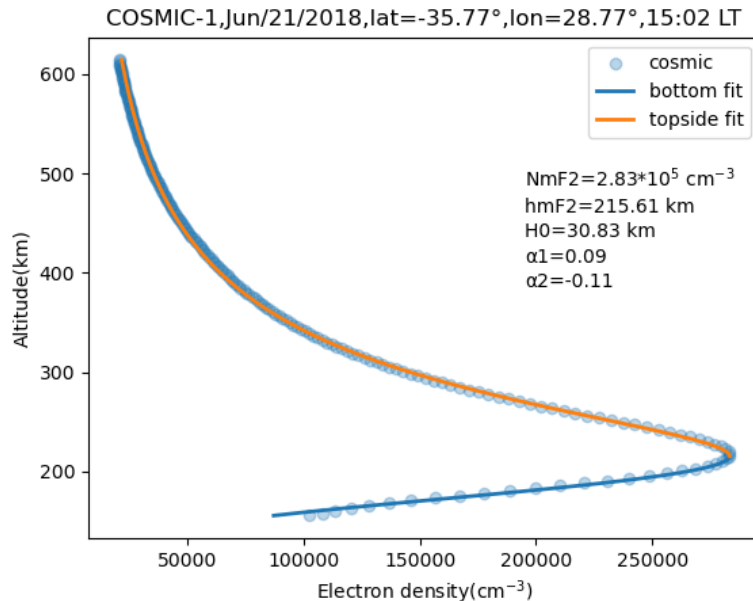


3D electron density modeling based on deep learning

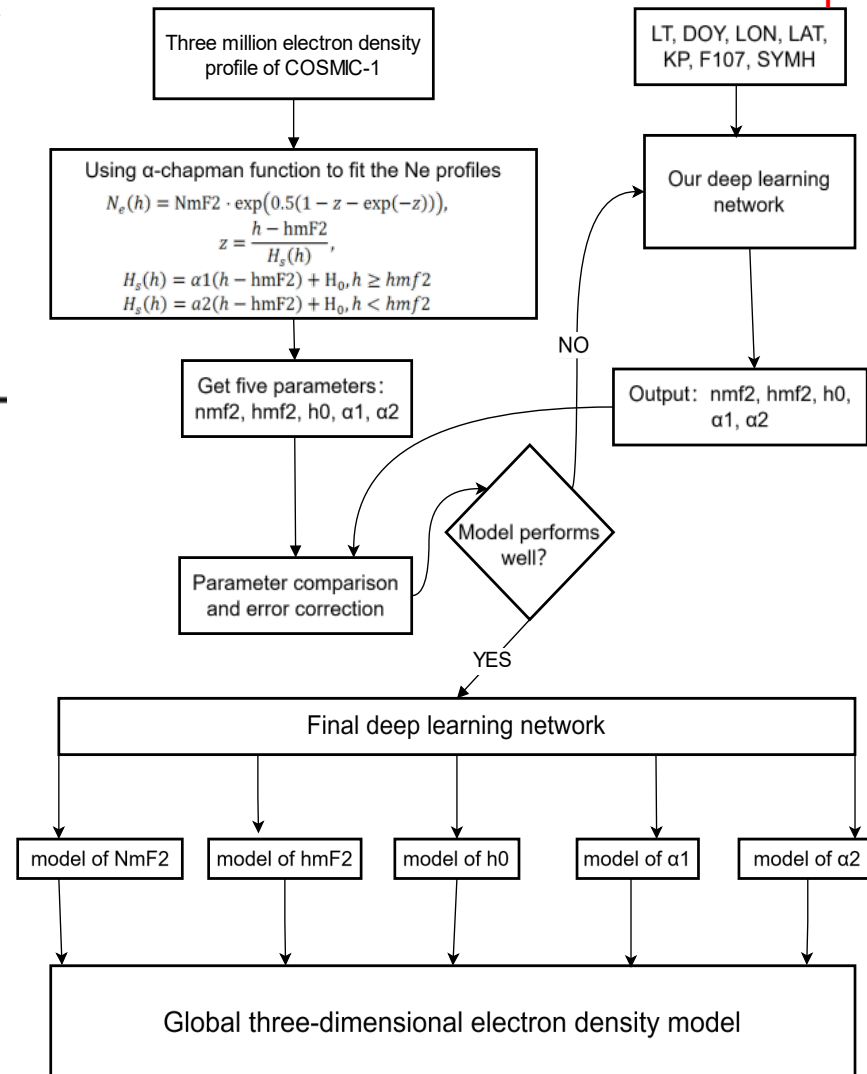


Five parameters, NmF2, hmF2, H0, α_1 , and α_2 , were obtained by fitting the α -chapman function

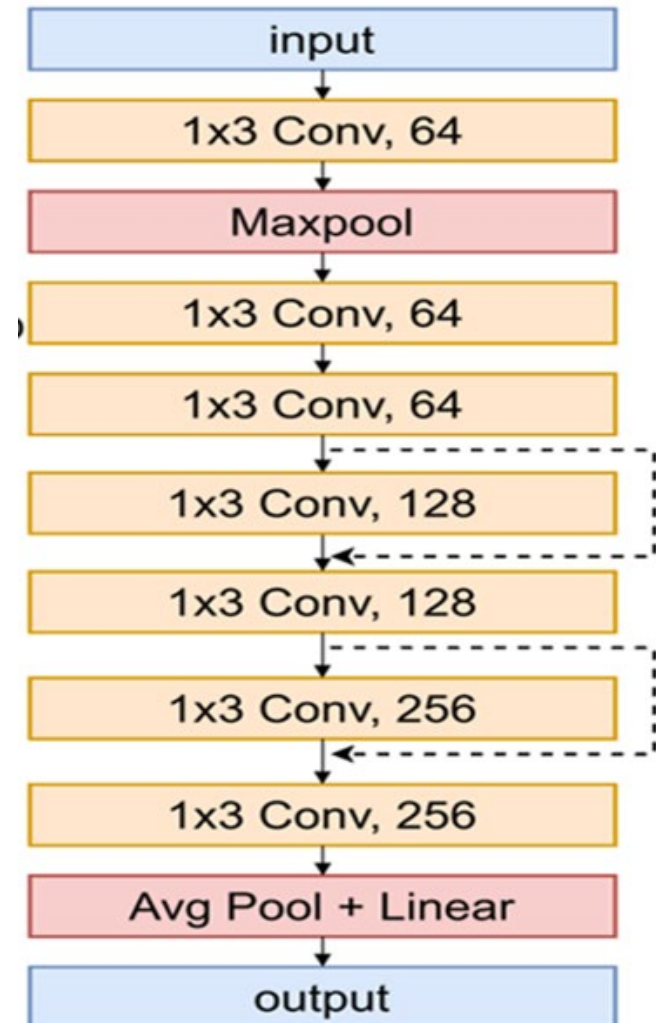
$$N_e(h) = \text{NmF2} \cdot \exp(0.5(1 - z - \exp(-z))),$$
$$z = \frac{h - \text{hmF2}}{H_s(h)},$$
$$H_s(h) = \alpha_1(h - \text{hmF2}) + H_0, h \geq \text{hmF2}$$
$$H_s(h) = \alpha_2(h - \text{hmF2}) + H_0, h < \text{hmF2}$$



Flowchart of the training input



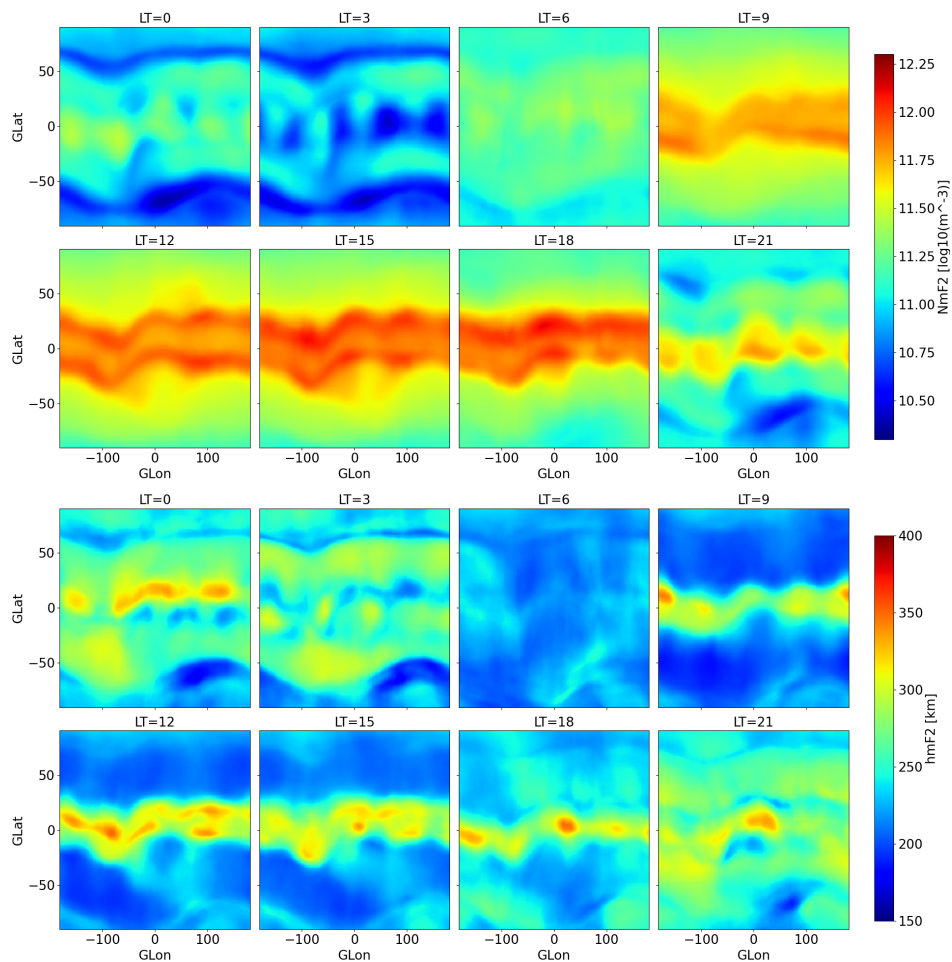
Interior design of the model



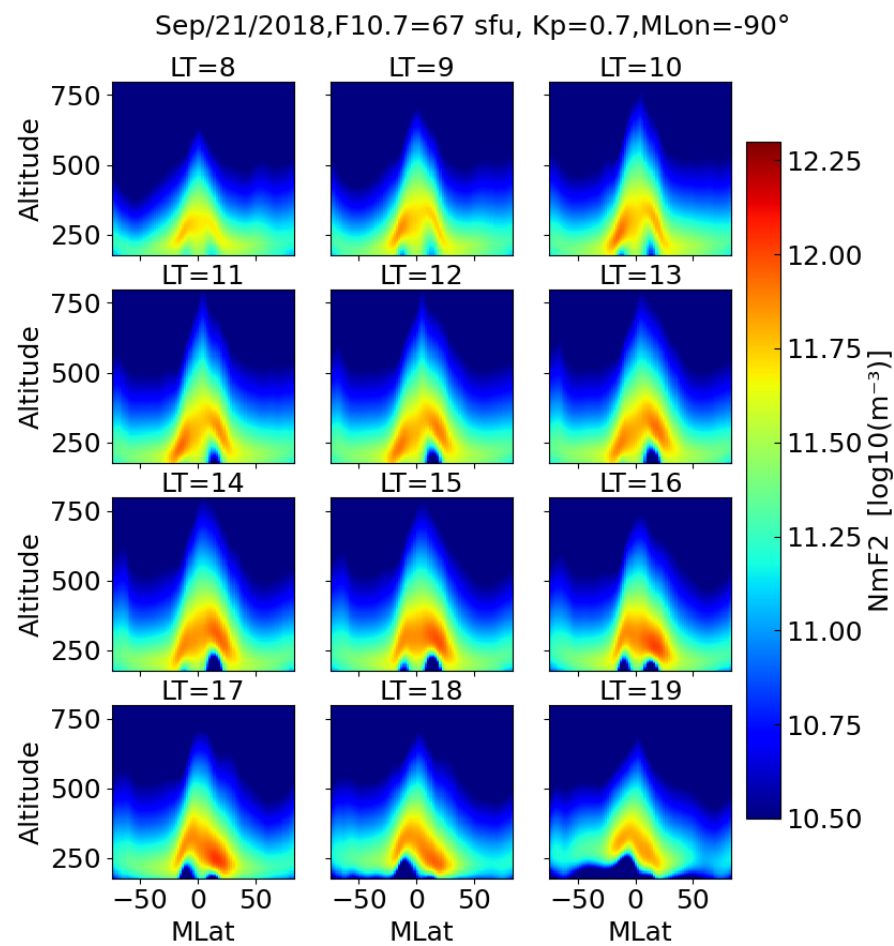
3D electron density modeling based on deep learning



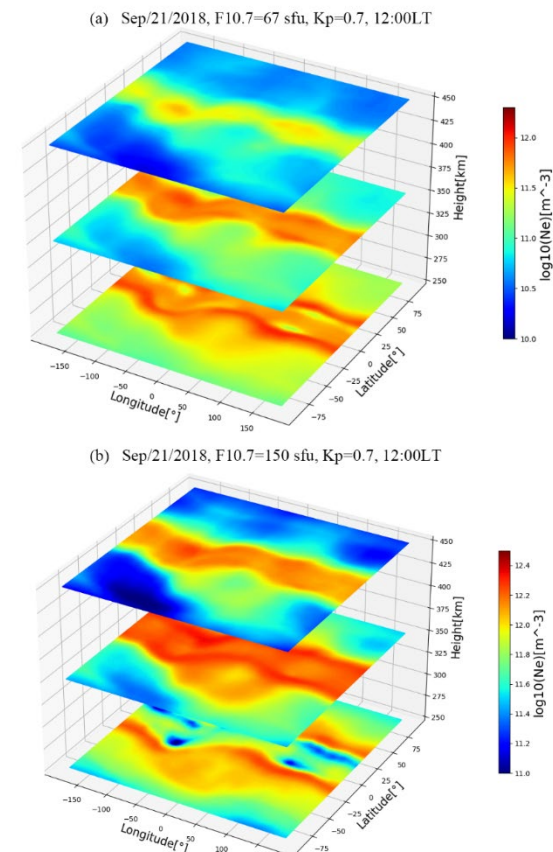
Glat versus Glon distribution in different LT



Altitude versus Mlat distribution in different LT



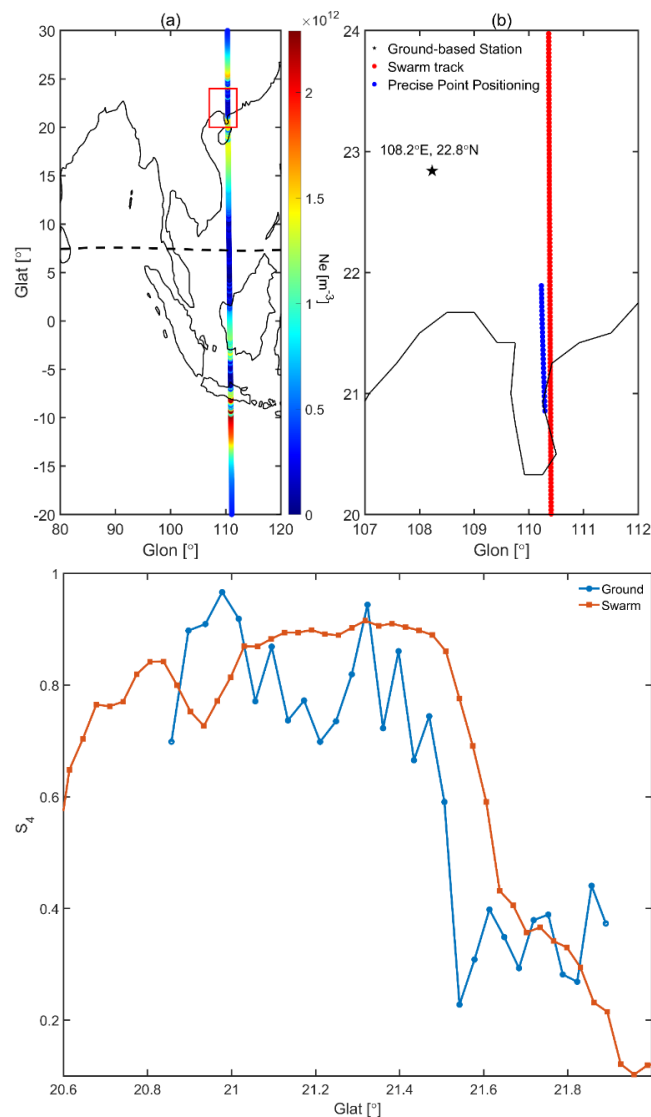
Under different solar activity condition



Phase screen modeling

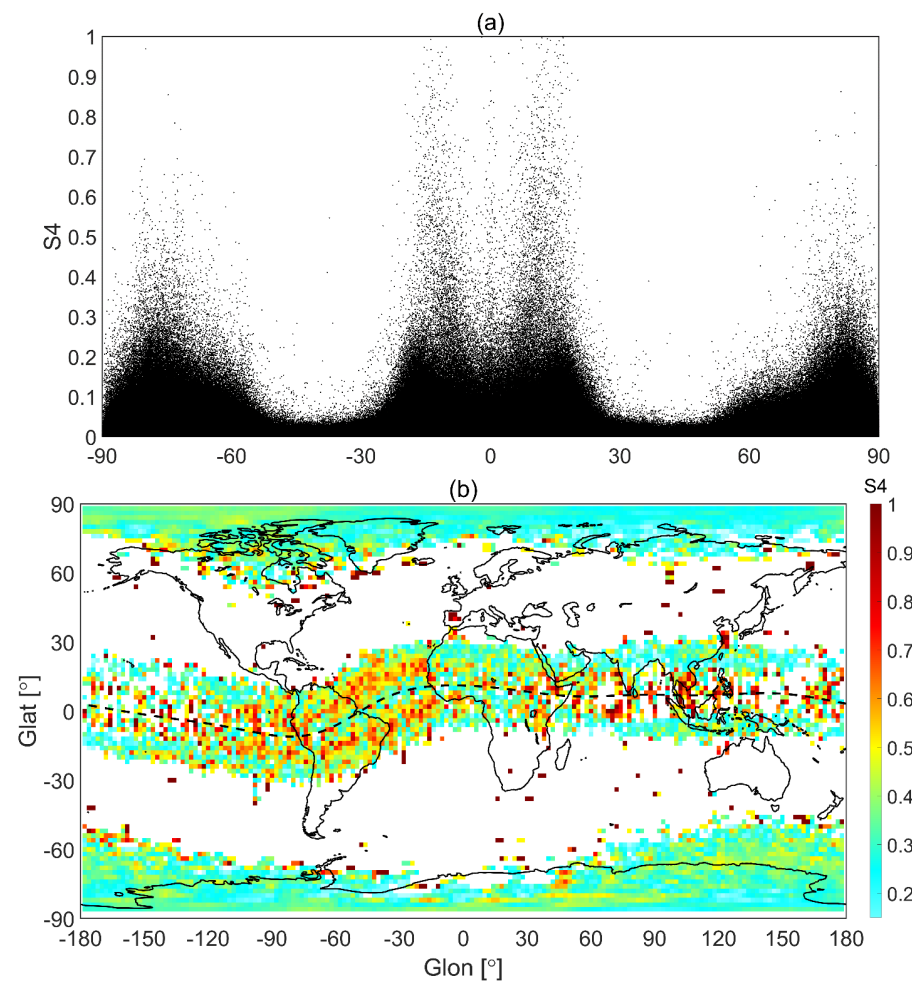


Comparison Results with Ground-Based Stations



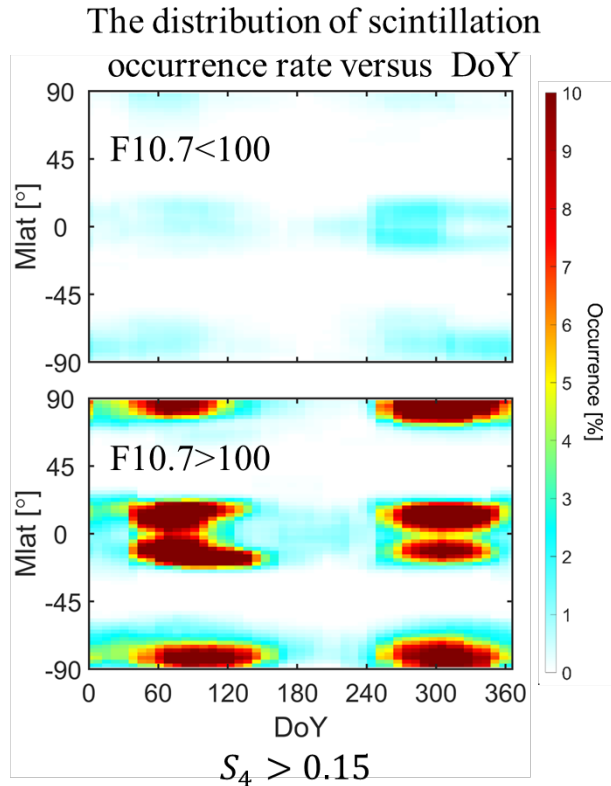
Global Phase Screen Scintillation Results

Global Ionospheric Scintillation Analysis Using Swarm Satellite Data (2014–2023)

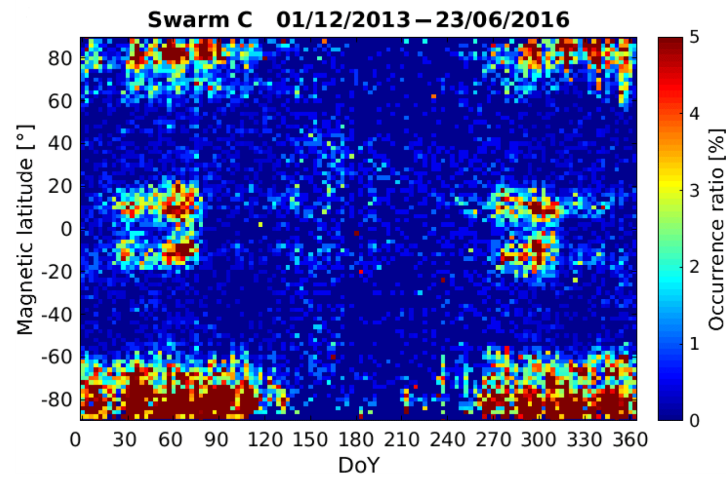




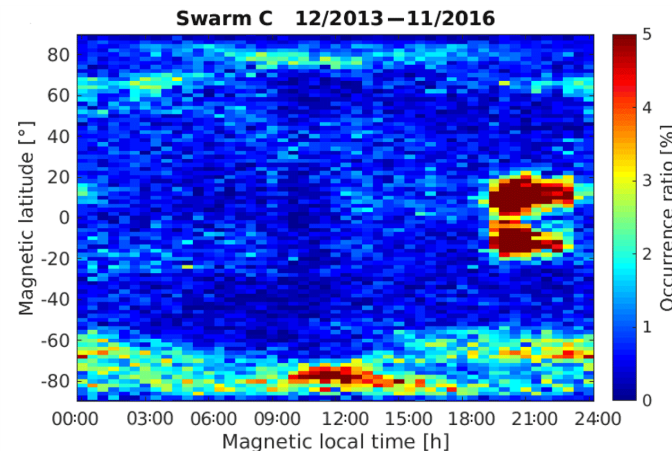
The distribution of Swarm GPS loss-of-lock occurrence rate versus DoY



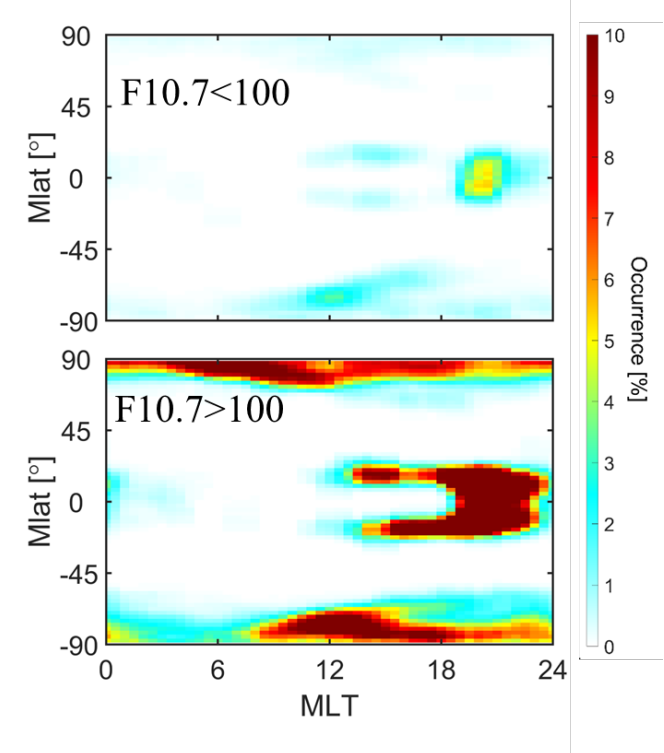
The highest occurrence rates are primarily observed during the equinoctial periods



(Xiong, et al., 2018)



The distribution of scintillation occurrence rate versus MLT



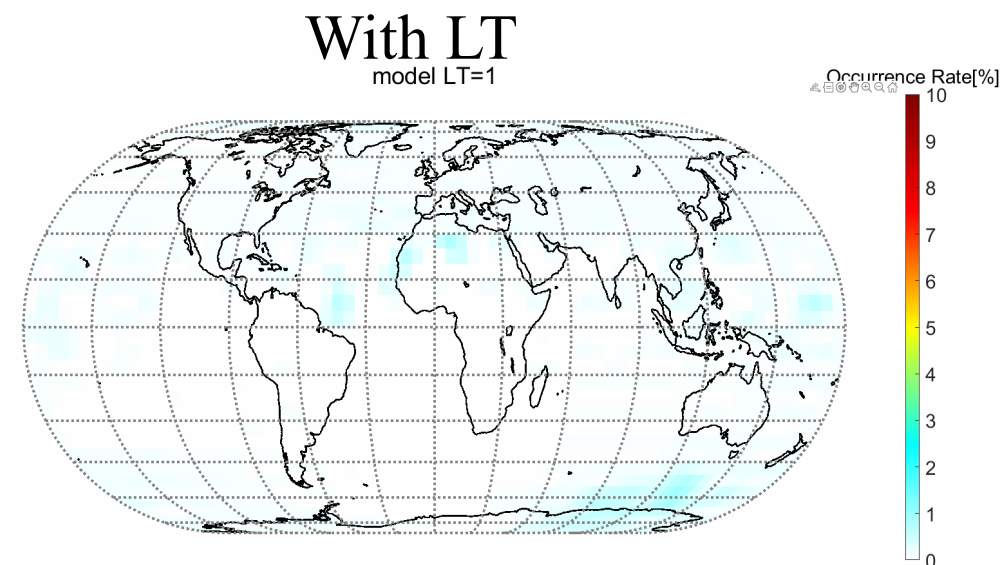
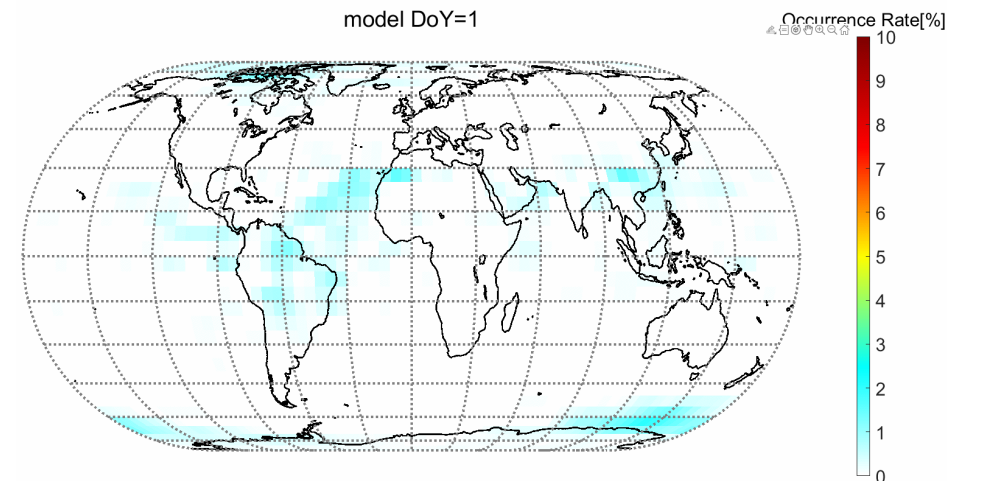
The peak occurrence rate in low-latitude regions is primarily observed around 21:00 local time

Construction of empirical model of Scintillation



$$OR = f_1(DoY) \cdot f_2(LT) \cdot f_3(F10.7) \cdot f_4(glon) \cdot f_5(glat)$$

$$\left\{ \begin{array}{l} f_1(x) = a_0 + \sum_{j=1}^3 \left\{ a_{2j-1}(j) \cdot \cos\left(\frac{j \cdot 2\pi \cdot x}{365.25}\right) + a_{2j}(j) \cdot \sin\left(\frac{j \cdot 2\pi \cdot x}{365.25}\right) \right\} \\ f_2(x) = b_0 + \sum_{j=1}^3 \left\{ b_{2j-1}(j) \cdot \cos\left(\frac{j \cdot 2\pi \cdot x}{24}\right) + b_{2j}(j) \cdot \sin\left(\frac{j \cdot 2\pi \cdot x}{24}\right) \right\} \\ f_3(x) = \sum_{i=0}^2 c_i x^i \\ f_4(x) = g_0 + \sum_{j=1}^{18} \left\{ g_{2j-1}(j) \cdot \cos\left(\frac{j \cdot 2\pi \cdot x}{360}\right) + g_{2j}(j) \cdot \sin\left(\frac{j \cdot 2\pi \cdot x}{360}\right) \right\} \\ f_5(x) = h_0 + \sum_{j=1}^{18} \left\{ h_{2j-1}(j) \cdot \cos\left(\frac{j \cdot 2\pi \cdot x}{180}\right) + h_{2j}(j) \cdot \sin\left(\frac{j \cdot 2\pi \cdot x}{180}\right) \right\} \end{array} \right.$$



List of Publications



	Supported by the Dragon 6 cooperation 2024–2028 (Project No. 95437)		
	Author	Title	DOI
1	XinYi Rang, Chao Xiong , et al.	Comprehensive evaluation of the vector magnetic field data from Macau Science Satellite-1A	10.26464/epp2025038
2	Yuhao Zheng, Chao Xiong , et al.	Global Ionospheric Scintillation Estimation Based on Phase Screen Modeling From One - Dimensional Satellite Data	10.1029/2024SW004103
3	Qian Pan, Chao Xiong , et al.	Interpretable machine learning for thermospheric mass density modeling using GRACE/GRACE-FO satellite data	10.1029/2024SW004259
4	Shunzu Gao, Chao Xiong , et al.	Predicting equatorial spread F at JICAMARCA sector via supervised machine learning	10.1029/2024SW004214
5	Shunzu Gao, Chao Xiong , et al.	Altitudinal variation of O+ scale height at the equatorial topside ionosphere	10.1029/2024JA033033
6	Yuyang Huang, Chao Xiong , et al.	Characteristics of Equatorial Electrojet Derived From MSS1A Observation: Initial Result	10.1029/2024EA004096
7	Chao Xiong , Yuyang Huang et al.	Responses of the Ionospheric Zonal Currents From Equator to Middle Latitudes During the Intense Geomagnetic Storm on 10–12 May 2024	10.1029/2025JA033992

Thank you for your attention!